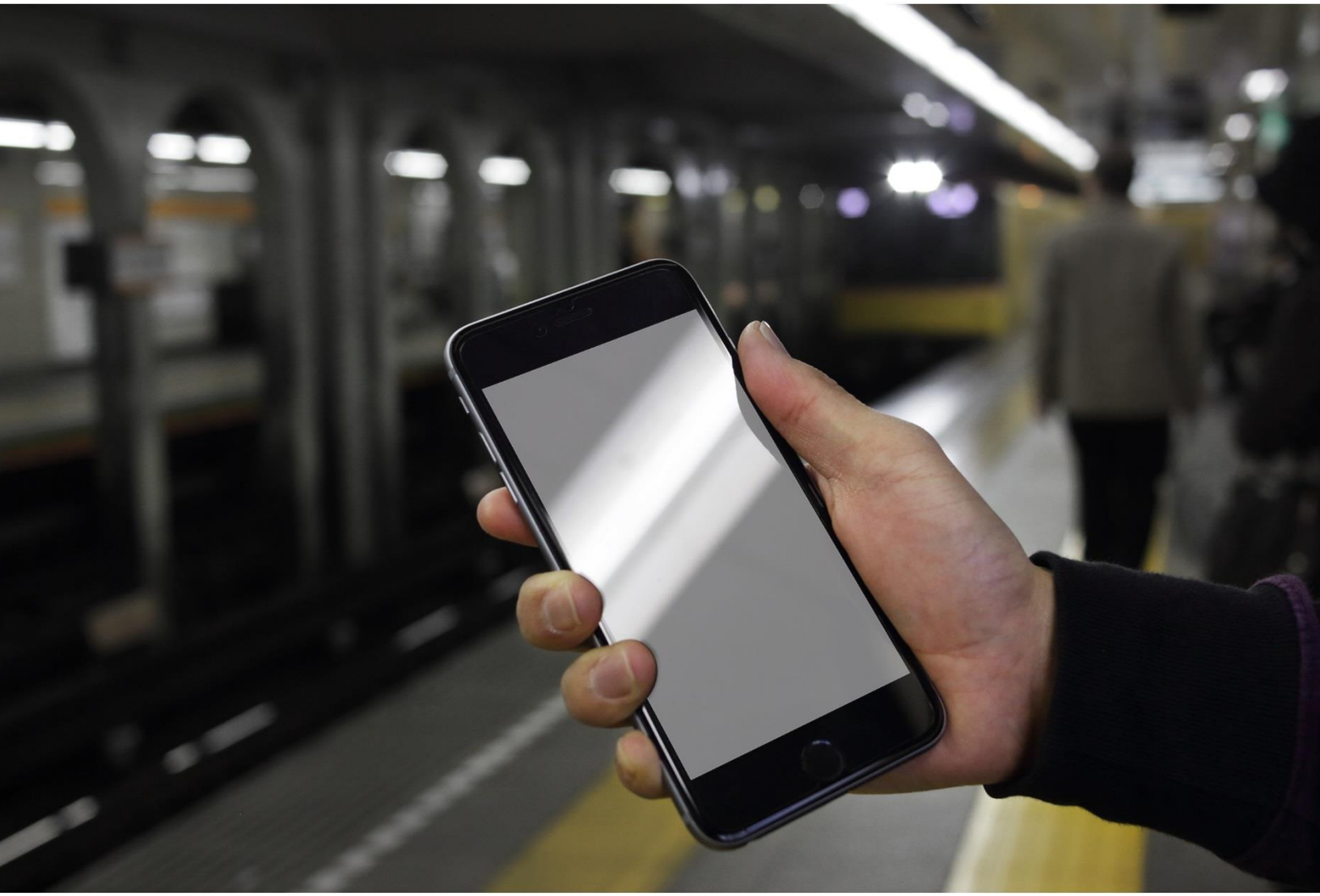
Wi-Fi and LTE-U 2017



MOBILE EXPERTS

Abstract:

This report provides a comprehensive forecast for Carrier Wi-Fi, LAA, LWA, and LTE-U deployment. Cost analysis for each option is considered for scenarios involving mobile operators, cable operators, OTT players, and enterprises.

The impact of LTE-U on the Enterprise Wi-Fi market is also considered in detail. CBRS systems in the USA are considered in multiple scenarios.

A five-year forecast of access points is provided with multiple technical, regional, and business level breakdowns for detailed insight into the LTE-U opportunity.

Kyung Mun

July 2017

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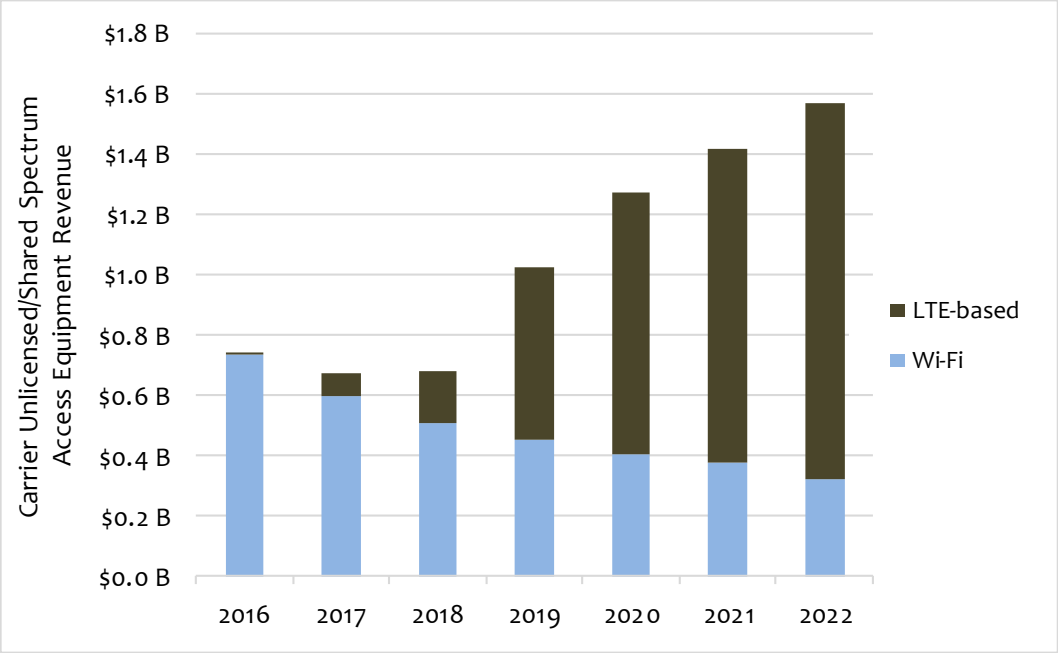
CARRIER WI-FI and LTE-U:
Increasing Technology Choices for Carrier (and Enterprise) Services in Unlicensed and Shared Spectrum Bands

MEXP-LTEU-17
July 2017

1 EXECUTIVE SUMMARY

Carrier and public wireless services in the unlicensed bands have, up to this point, been supported by Wi-Fi technology. While it generally provides low-cost network solutions, due to its vast scale, Wi-Fi has been unsatisfactory -- especially for mobile operators who seek better control of wireless services running over the unlicensed bands. Over the past few years, the mobile industry has been working toward several 3GPP standard-based approaches to better leverage the unlicensed spectrum including LAA, LWA, MulteFire, and CBRS (in the United States). As the ecosystems have matured, the LTE-based unlicensed technologies including LAA and LWA are beginning to make impact. Operators have begun to deploy these technologies as a part of their small cell densification efforts. With the forecasted deployment of LTE-based technologies in the unlicensed and shared bands, the overall "LTE-U and Carrier Wi-Fi" market is poised to grow at about 20% CAGR (2017-2022) to reach $1.6B in 2022. Excluding the Carrier Wi-Fi segment, the LTE-based portion of the market is expected to grow from less than $75M in 2017 to about $1.25B in 2022.



Source: Mobile Experts

Chart 1: Carrier Unlicensed/Shared AP Revenue Forecast, LTE-based vs. Wi-Fi, 2016-2022

With mobile operator preference for LTE-based solutions, the Carrier Wi-Fi market is expected to trend down. While the cable operators and other OTT providers like fixed wireless ISPs in rural areas are likely to continue the support for Wi-Fi, mobile operators are clearly choosing LTE-based solutions. Among the LTE-based solutions, mobile operators appear to favor LAA as it provides the most seamless path to so-called "Gigabit LTE" services in which multiple carriers are aggregated to achieve higher user speeds. As operators in advanced markets upgrade to LTE-Advanced Pro, those with limited spectrum

holdings will be able to aggregate unlicensed channels with LAA small cells in hotspot locations.

While LWA and LWIP have been designed to offer solutions for operators looking to extend the life of existing Wi-Fi infrastructure, they appear less relevant to most major operators. Even for mobile operators with mature Wi-Fi footprint, the effective lifespan of deployed Wi-Fi infrastructure may have already passed. In such cases, operators may simply deploy LAA small cells instead of upgrading to next-generation Wi-Fi. LWA and LWIP have burdensome costs associated with core network changes and updates required on Wi-Fi access points that may be too great for operators to adopt. For this reason, Mobile Experts currently forecasts a tepid uptake for LWA and LWIP. Between the two solutions, LWA is more likely solution to be adopted as LWIP has significant costs associated with core network changes and network performance -- not to mention the added complexity on devices to handle multipath TCP, which will negatively impact battery life on devices.

Meanwhile, a battle is brewing over the new CBRS band in the United States. With novel licensing rules to foster spectrum sharing, the CBRS band has garnered strong interest from myriad stakeholders including cable operators, mobile operators, and OTT/neutral host service providers. While possible rule changes may raise a barrier to entry for smaller players, CBRS small cell deployments are expected in 2018-2019 timeframe by the cable operators and possibly some mobile operators as well.

The unlicensed and shared spectrum segment of the carrier infrastructure market is undergoing rapid changes as new technologies, new spectrum, and heightened competition between cable and mobile operators are incentivizing multiple players to stake a claim. The battle for "mid-band" unlicensed and shared spectrum may be a prelude to 5G network buildouts from operators of all strife. Spectrum is the "life blood" of the mobile industry, and operators are happy to "acquire" spectrum through auctions or by deploying small cells to take advantage of the unlicensed and shared spectrum bands.

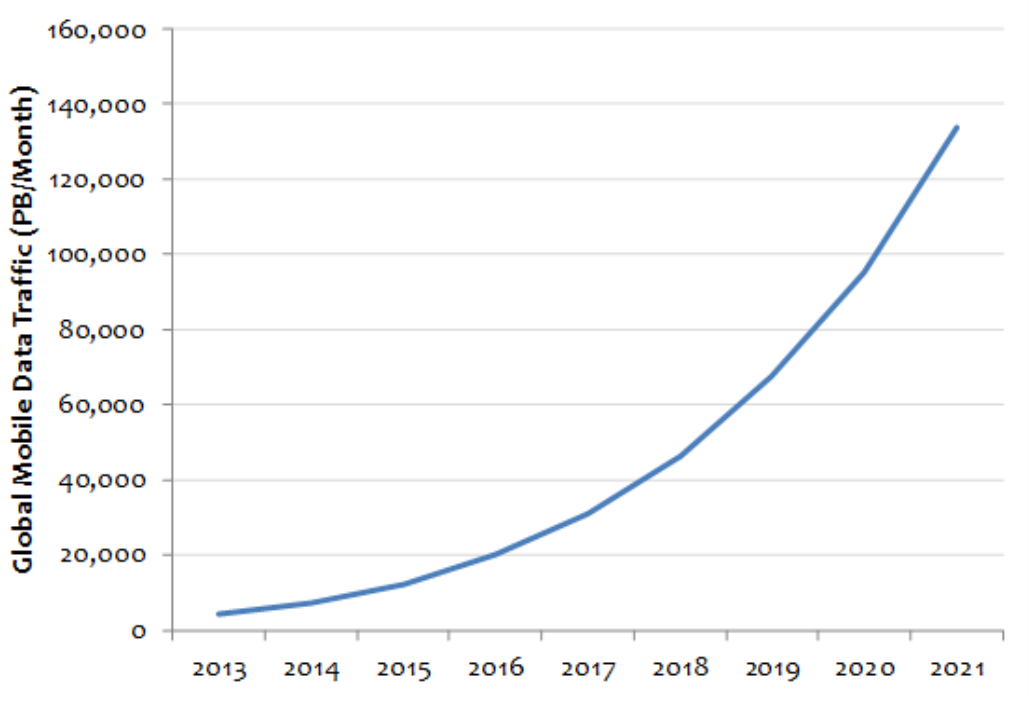
2 MARKET DRIVERS

A fundamental driver of the carrier infrastructure market is the underlying mobile data traffic growth. For the carrier infrastructure segment targeting unlicensed and shared spectrum, a few additional market drivers are at play:

1) LTE-Advanced Pro network upgrades, i.e., "Gigabit LTE" upgrades, are happening;
2) Some operators lack licensed spectrum for high-count Carrier Aggregation (i.e., spectrum scarcity in "mid" band);
3) In the United States, the new CBRS shared spectrum is opening new opportunities;
4) "LTE-unlicensed" ecosystem is maturing; and,
5) Competition for subscribers and underlying spectrum and technology assets is happening across mobile and cable industries.

Mobile Data Tsunami – Demand Remains Strong

The mobile data traffic growth continues at a strong pace, with 60% data traffic growth every year. According to the recent Ericsson Mobility June 2017 Report, the total traffic on mobile networks increased 70% year-over-year at the end of Q1 2017. While the incremental bump in traffic growth this year is partly due to Reliance Jio's aggressive introductory offer, the underlying demand for mobile data remains firmly intact.



Source: Mobile Experts, Cisco, Ericsson, Mobidia

Figure 1. Global Mobile Data Traffic Growth

The sheer weight of mobile traffic is a huge burden on the macro network, but it's important to note that a great deal of the data growth is taking place in very specific locations. Data demand is often very spotty, with key public venues such as stadiums and transportation hubs experiencing very high data traffic density, while the data demand at other places like suburban neighborhoods does not see the same growth. The "spotty" nature of traffic hotspots has partly accelerated small cell growth as operators target capital expenditure plans to these traffic hotspots instead of broadly activating carrier across their entire network footprint.

Need for Speed – "Gigabit LTE"

In addition to the operator strategy of targeted capacity augmentation through small cells, consumers are demanding more speed. With introduction of Category 16 UE devices such as Samsung Galaxy 8, "Gigabit LTE" marketing hype has already started in some markets as operators roll out LTE-Advanced Pro features (i.e., 3 Carrier Aggregation along with 4x4 MIMO and 256 QAM modulation to achieve a theoretical peak, single-user throughput of 1 Gbps). For example, Telstra in Australia earlier this year launched its "Gigabit LTE" home broadband service using Netgear's mobile broadband router based on Category 16 modem (see Figure 2).

Source: Netgear (website posting)

Figure 2. "Gigabit LTE" Marketing Has Begun

According to Global Mobile Supplier Association (GSA), 19 operator networks in 15 countries are already enabled for LTE-Advanced Pro.[1] With smartphone replacement cycles ranging from 18-24 months in developed markets, higher-category smartphone devices capable of 3-4 carrier aggregations will eventually proliferate in the market. With small cell deployments in strategic locations, operators will be able to turn on Carrier Aggregation to increase capacity and boost user throughput speeds. For operators with limited licensed spectrum

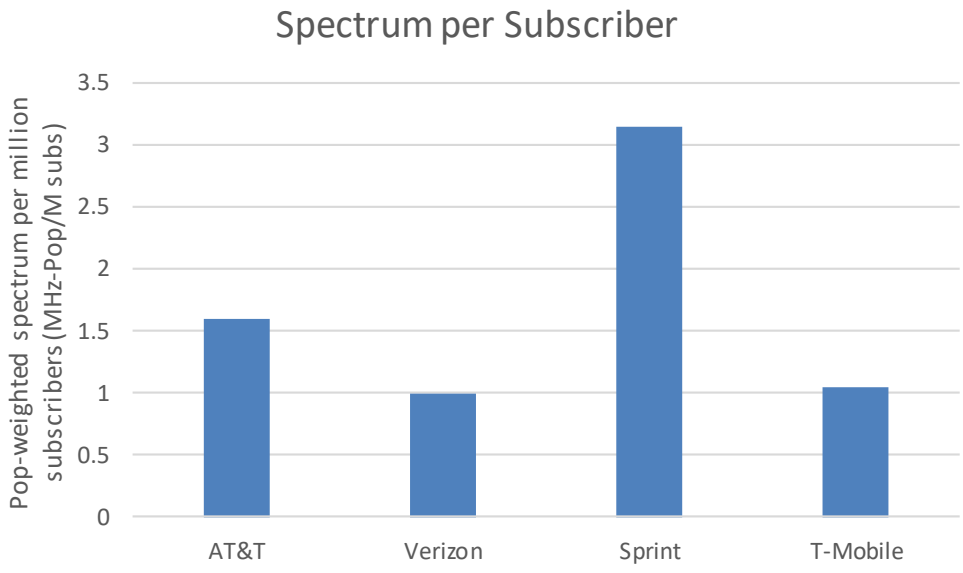
[1] As of May 2017

holdings, the unlicensed and shared bands provide readily available spectrum for a high-count Carrier Aggregation especially in urban outdoor settings where 5GHz unlicensed use is likely limited.

Spectrum Scarcity and Small Cells

Major operators in advanced mobile markets are coming to realization that wireless densification is inevitable as licensed spectrum bands between 1-3GHz have been mostly auctioned off. As the industry looks towards very high millimeter wave bands for 5G in the 2020 timeframe, the industry is looking to harness the sub-6GHz unlicensed and shared bands for an immediate relief from capacity exhaustion and network congestion. If densification and small cell deployments are inevitable and necessary, why not take advantage of the shared and unlicensed spectrum in the 3.5GHz and 5GHz bands now? With regulatory power limits, the unlicensed bands are naturally positioned for small cell deployments.

In a world of "Gigabit LTE" where consumer expectation for high-speed mobile broadband connectivity is often fueled with complicit marketing, one can reason that the unlicensed and shared spectrum bands are expensive spectrum assets to enable "Gigabit LTE" services. As shown below, some U.S. operators are more spectrum-starved than others and is more inclined to deploy LTE-U/LAA small cells. In fact, T-Mobile has already announced that it has gone live with LTE-U operation in select markets and is actively expanding the rollout to other markets.[2]



Source: Mobile Experts

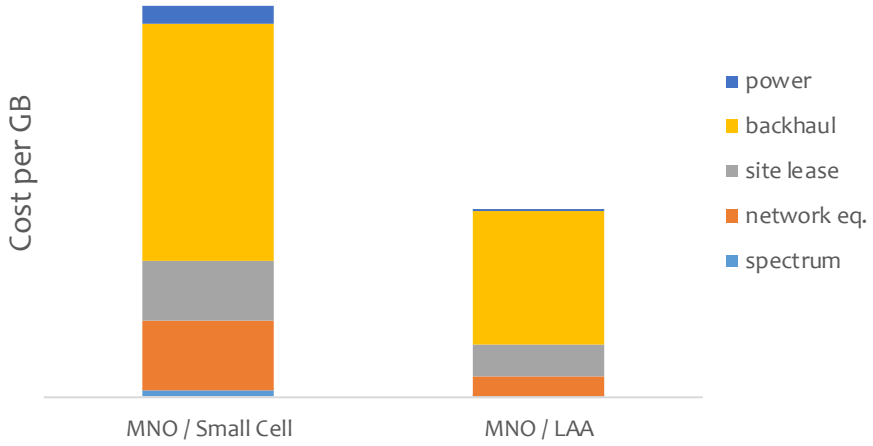
Figure 3. USA Spectrum per Subscriber - Scarcity or Abundance

[2] FierceWireless, "T-Mobile takes LTE-U crown, launches in select locations," June 26, 2017.

Unlicensed LTE Technologies – Mobile Industry's Fracking Moment

Fracking, or more specifically hydraulic fracturing, has revolutionized the oil industry by enabling oil producers to more economically extract natural gas and petroleum trapped in deep rock formations. The fracking technology has allowed producers to reopen abandoned oil fields as the technology has made abandoned oil fields to valuable again.

Similarly, the unlicensed LTE technologies like LTE-U/LAA and LWA allows the mobile operators to "mine" the unlicensed and shared spectrum bands with more advanced technologies such as "listen before talk" (LBT) coexistence to take advantage of the unlicensed spectrum bands more effectively for LTE services. With Carrier Aggregation, LTE-U/ LAA small cells enable higher effective cell capacity. By our estimate, LTE-U/LAA small cells can effectively halve the unit cost of delivering a Gigabyte (cost per GB) over LAA small cells versus traditional small cell using licensed spectrum.



Source: Mobile Experts

Figure 4. Cost per GB of Traditional Licensed Small Cell vs. LAA

The LTE-U/LAA and LWA technologies effectively allows the mobile operators to opportunistically leverage unlicensed spectrum for LTE services, where before running LTE services on unlicensed spectrum was not possible.

Competition for Subscribers, Spectrum, and Technology

In today's marketplace where communication and entertainment services are increasingly delivered over IP in either fixed or mobile context, the stark premium given to mobile access over fixed (i.e., 20-60x more in terms of $ per GB consumed) is bound to cause fixed operators to covet the mobile wireless business.[3] We have seen increasing competitive positioning of cable operators towards mobile business despite its many challenges ranging from viability of MVNO business model to a significant working capital required for handset

[3] http://www.fiercewireless.com/story/kyung-9-gb-mobile-internet-20-60x-premium-fixed-internet/2016-06-20

inventory, etc. Despite the challenges, we have seen, over the course of past couple of years, cable operators' increasing investment in Wi-Fi hotspots; a pursuit of yet another spectrum purchase, and a decision to pursue an MVNO business model.[4]

The mobile operators have also responded in kind. In the USA, AT&T has acquired a satellite Pay TV provider, DirecTV, to more effectively compete against cable operators in the video market, and Verizon has mentioned its intention to pursue a fixed wireless play with its upcoming "5G" launch, in direct competition against one of cable operators' core businesses. In Europe, we have seen more direct competition between fixed and mobile operators in pursuit of "quad play" services where operators bundle fixed and mobile service offerings to attract new customers, and more importantly to reduce churn. For example, a fixed operator (BT) acquired a leading mobile operator (EE) in the UK as a direct consequence of these competitive market dynamics.

In a highly competitive environment, the use of unlicensed bands by both fixed and mobile operators is likely to intensify as the operators look to achieve ever lower unit costs in delivering mobile data. Not having to pay for spectrum will certainly help in this regard.

CBRS – New Spectrum, New Players, and New Opportunities

Considering that a major US mobile operator holds, on average, roughly 130 MHz of licensed spectrum, the 150 MHz of new spectrum in the 3.5 GHz CBRS band is a significant asset for further capacity expansion. In addition, the flexible three-tier licensing framework is expected to lower the barrier and promote success-based investments by new entrants. CBRS opens up new use cases; and, encourages business innovations from traditional operators and new entrants alike.

Here is a list of possible opportunities that CBRS can enable for the different stakeholders:

1) Mobile operators can leverage CBRS band as a secondary carrier in LAA deployment to augment network capacity and boost user throughput speed;
2) Cable operators can build LTE networks and leverage that capacity in their MVNO business to minimize or offset MVNO rent costs;
3) Neutral host providers can use CBRS band to stand up LTE networks for in-building wireless services directly to enterprises or to mobile operators for resell;
4) Enterprises can build "private LTE" networks on the CBRS band under GAA or PAL basis with the assumption that PAL licensing costs are not too exorbitant.

The novel three-tier licensing approach encourages the stakeholders to pursue those business opportunities as highlighted above without the burden of high upfront costs for traditional licensed spectrum. Stakeholders can purchase PAL licenses at a later date to

[4] The cable industry bought AWS spectrum under the SpectrumCo consortium which was eventually sold to Verizon with a provision for an MVNO which Comcast has used to launch its Xfinity mobile service.

secure an appropriate amount of spectrum at specific geographic locations to offer wireless services. This type of success-based investment in PAL spectrum licensing attempts to allow efficient use of the band.

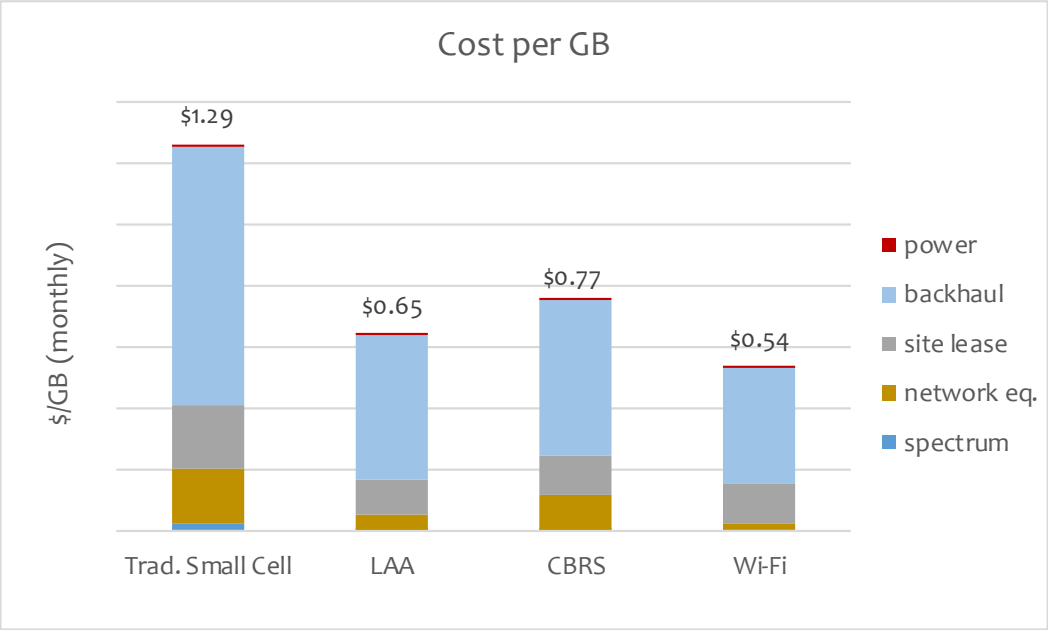
3 MARKET OVERVIEW

As mobile operators continue to battle data-traffic growth challenges and seek cost-effective solutions to meet ever-increasing demands and expectations of consumers, the maturing technology ecosystems such as LTE-U/LAA, CBRS, and MulteFire are a welcome relief. Until the millimeter wave band ecosystem matures, the unlicensed 5GHz and shared 3.5 GHz bands represent near-term spectrum opportunities upon which to run LTE services. With the relevant 3GPP standards completed and device and infrastructure ecosystems quickly maturing, operators have many options to consider as they begin to leverage the unlicensed and shared bands with LTE in route to 5G NR transition.

Economics of LTE-U/LAA, CBRS, and Wi-Fi

The economics of leveraging unlicensed spectrum vary by technology, and target use cases. There are many factors that attribute to an operator choosing one technology over others. The decision can vary by specific regions within the operator's footprint as well. For instance, an operator with a limited spectrum holding is more likely to consider LTE-U/LAA small cells to leverage the 5GHz unlicensed or CBRS bands. On the other hand, an operator with extensive and mature Wi-Fi footprint may consider LWA in order to maximize its Wi-Fi investments. For others with a large inventory of licensed spectrum (e.g., Sprint with 2.5 GHz spectrum), LTE-unlicensed technologies like LAA offer little value. Sprint has enough spectrum, just not enough capital to deploy that spectrum.

There are many factors to consider in network technology choices, including operational complexity, internal process coordination, device ecosystem impact, etc. Understanding basic unit economics is a good place to start. The below figure shows the unit costs of delivering a Gigabyte (GB) of data over a traditional small cell using licensed spectrum vs. a list of unlicensed technologies including LAA vs. CBRS vs. Carrier Wi-Fi. The unit cost advantages of unlicensed technologies (LAA, CBRS and Wi-Fi) over traditional licensed small cell stem from a simple fact that free or cheap unlicensed/shared bands can be used to increase effective cell capacity. The slightly higher unit cost of CBRS vs. LAA and Wi-Fi, is due to higher equipment cost associated with SAS burdened cost. Overall, the unit cost of delivering a GB of mobile data using unlicensed and shared spectrum technologies can be about one-half the cost of using a traditional small cell using licensed spectrum.



Source: Mobile Experts

Figure 5. Comparative Cost per GB of LAA vs. CBRS vs. Wi-Fi

The following assumptions are used to calculate the monthly $/GB unit costs for the different unlicensed technologies. The one-time CAPEX line items such as spectrum and radio equipment costs are converted into monthly costs based on estimated depreciation schedule of the line items.

Traditional Licensed Small Cell		
Element	**Cost estimate**	**Notes**
Spectrum cost	$2,800	$1.75/MHz-pop average cost based on recent AWS spectrum auction; 20-year depreciation
Radio equipment	$5,000	LTE BBU/RRH combo; 5-year depreciation
Site lease	$100/month	avg. cost of muni pole attach cost in top US markets
Backhaul	$400/month	2-strand dark fiber cost or high-capacity lit service
Power	$4/month	Based on 20-50W base station power consumption
Effective Cell capacity	475 GB/month	Max. cell capacity with 6% average monthly utilization rate (small cells are more peaky than macro since they have smaller footprints)

Source: Mobile Experts

Figure 6. Cost Assumptions for Traditional Small Cell 'Cost per GB' Calculation

LTE-U/LAA Small Cell		
Element	**Cost estimate**	**Notes**
Spectrum cost	$560	10x10 FDD LTE with 40MHz of unlicensed spectrum; variable spectrum cost is lower than traditional Small Cell case as LAA footprint is smaller, thus less subscribers; 20-year depreciation schedule
Radio equipment	$2,500	LAA multiband radio; 5-year depreciation
Site lease	$100/month	avg. cost of muni pole attach cost in top US markets
Backhaul	$400/month	2-strand dark fiber cost or high-capacity lit service
Power	$4/month	Based on 20-50W base station power consumption
Effective Cell capacity	854 GB/month	Max. cell capacity based on 54Mbps of LAA coexistence throughput (from NI testing) with 5% average monthly utilization rate

Source: Mobile Experts

Figure 7. Cost Assumptions for LTE-U/LAA 'Cost per GB' Calculation

CBRS Small Cell		
Element	**Cost estimate**	**Notes**
Spectrum cost	$200	Estimated $0.30/MHz-pop for PAL license
Radio equipment	$2,500	CBRS small cell; 5-year depreciation
Site lease	$100/month	avg. cost of muni pole attach cost in top US markets
Backhaul	$400/month	2-strand dark fiber cost or high-capacity lit service
Power	$4/month	Based on 20-50W base station power consumption
Effective Cell capacity	475 GB/month	Max. cell capacity with 5% average monthly utilization rate

Source: Mobile Experts

Figure 8. Cost Assumptions for CBRS 'Cost per GB' Calculation

Carrier Wi-Fi		
Element	**Cost estimate**	**Notes**
Spectrum cost	$ 0	
Radio equipment	$1,000	Outdoor Wi-Fi unit; 5-year depreciation
Site lease	$100/month	avg. cost of muni pole attach cost in top US markets
Backhaul	$300/month	High-capacity ethernet link cost
Power	$3/month	Lower power consumption on Wi-Fi units
Effective Cell capacity	791 GB/month	Max. cell capacity with 5% average monthly utilization rate (expect larger footprint for high outdoor EIRP than LAA)

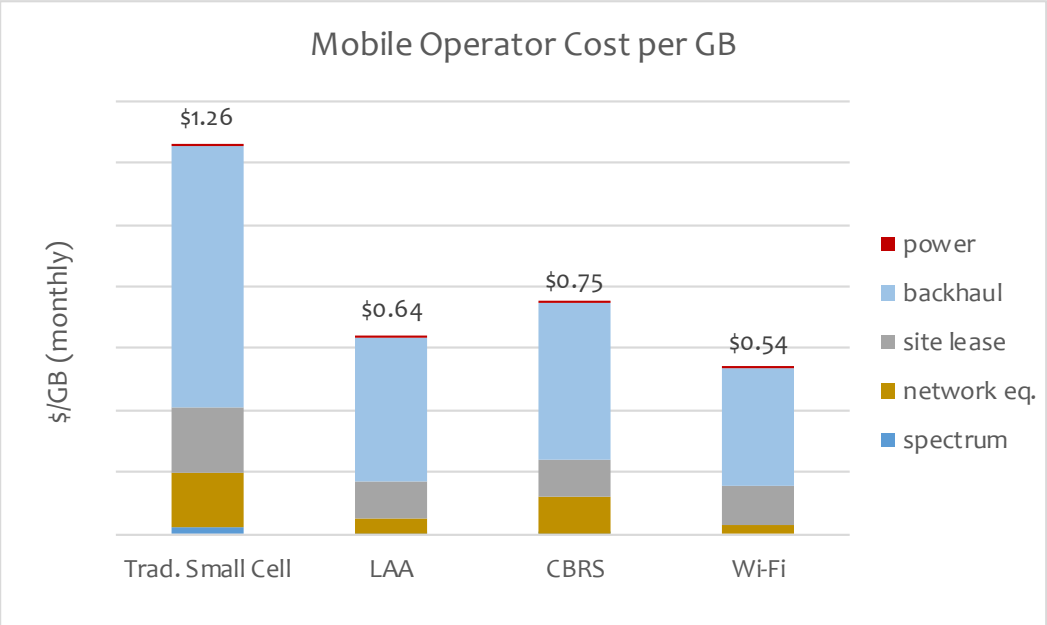
Source: Mobile Experts

Figure 9. Cost Assumptions for Carrier Wi-Fi 'Cost per GB' Calculation

Mobile Operator Perspective and Choices

Mobile operators in Asia have been at the forefront of carrier Wi-Fi deployments in the past as they looked for additional avenues to increase their wireless capacity. While Wi-Fi networks have been sufficient for the primary purpose of data offload, the standalone carrier Wi-Fi networks have proven inadequate in providing carrier-grade quality of service. Consistency of quality assurance via Wi-Fi has proven particularly elusive in dense environments. To better leverage the unlicensed bands, the mobile industry has drafted 3GPP standards to offer several options to better leverage the unlicensed bands including: LAA, LWA, and LWIP.

In terms of simple economics, a mobile operator can almost halve the unit cost of delivering a GB of data by leveraging unlicensed technologies. While the unit cost of delivering data over Wi-Fi is cheaper than LAA or CBRS, Carrier Wi-Fi has not proven to be an effective solution in a Wi-Fi offload setting. Moreover, managing separate LTE and Wi-Fi networks have proven to be cumbersome and operationally inefficient. Factoring in these factors, the total cost of ownership for Wi-Fi may be higher than the simple unit costs as outlined in the figure below.



Notes: 1) Assume that a mobile operator would 100% lease backhaul;
2) In case the operator uses owned fiber/fixed network for backhaul, the unit costs can significantly decrease

Source: Mobile Experts

Figure 10. Mobile Operator's Unit Cost of LAA vs. CBRS vs. Wi-Fi

Major mobile operators in Asia, North America, and Europe have carried out lab and field trials of LTE-U, LAA, and LWA over the past couple of years. Based on market activities, general market trends are emerging:

1) Mobile operators with limited Wi-Fi footprint are pursuing the LTE-U/LAA path;
2) Some operators in Asia-Pacific with mature Wi-Fi footprint are deploying LWA – but it is not clear yet that an operator like China Mobile with extensive Wi-Fi footprint will pursue LWA;
3) LWIP is no longer talked about as a viable option for most major mobile operators;
4) LAA is the preferred solution for most mobile operators seeking to leverage the unlicensed bands.

Mobile operators seem to prefer LTE-U/LAA as this technology option allows the operators to run LTE natively in unlicensed bands and still take advantage of existing LTE core networks including all aspects of service provisioning and delivery. Verizon and T-Mobile in the US have been vocal supporters of LTE-U/LAA, and as predicted in our 2016 report, T-Mobile has deployed LTE-U in select markets. We expect Verizon and AT&T to soon follow with live deployments. LTE-U small cells in live networks will be upgraded to LAA in 2018 via a software update. For mobile operators, LAA offers the most clear path to run LTE services on unlicensed bands. It does not impact core networking, and the unlicensed bands can be leveraged by deploying LAA small cells and introducing higher Category UE devices to aggregate multiple LTE carriers to increase throughput and network capacity overall.

Mobile Experts expects most U.S. mobile operators to choose LAA, and the market evidences point to this trend.

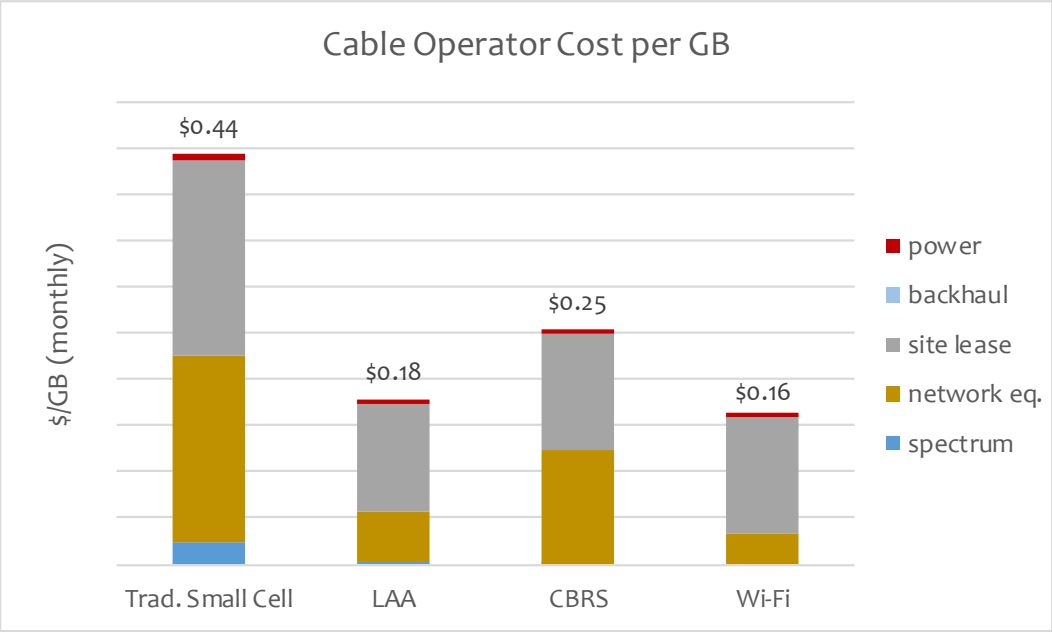
As predicted last year, some mobile operators in Asia-Pacific are beginning to deploy LWA. Chunghwa Telecom in Taiwan and M1 in Singapore has announced LWA deployments, but these are minor commercial rollouts at this stage. As per the previous discussion on challenges of LWA deployments, Mobile Experts believes that LWA is applicable to those who have extensive Wi-Fi footprint. China Mobile is a key case study and a big wildcard. Although we had expected China Mobile to deploy LWA this year, there has been no public evidence of this. Meanwhile, LWIP has faded into the background. It is no longer mentioned in mobile operator conversations as its impact on core networking seems too high for most operators to seriously consider.

While LWA also offers a means to aggregate LTE carriers over LTE and Wi-Fi infrastructure, it adds additional complexities. Not only do LTE eNodeB base stations need to be upgraded to support LWA, existing Wi-Fi access points must also be upgraded to support the feature. Not only that, UE client devices must also support LWA. This "trifecta" of interdependent upgrades may be too burdensome for many operators. For some operators, especially those in the United States with minimal Wi-Fi infrastructure under operation, deploying LTE-U/LAA as multiband small cell module seems to make the most sense.

Cable / Fixed Operator Perspective and Choices

Cable operators have been big proponents of Carrier Wi-Fi as they have built out public hotspots and homespots to complement their fixed broadband networks. To extend the wireless reach of fixed broadband services, cable operators have been placing outdoor Wi-Fi access points mounted on cable strands, and on street furniture. Although they seem committed to the outdoor Wi-Fi strategy for now, and publicly sing the praises of Wi-Fi, in private most cable executives will admit that LTE works better. They seem eager to run LTE on unlicensed and shared bands along with Wi-Fi. Mobile Experts believes that cable operators will deploy CBRS radios in 2018-2019 to take advantage of the new CBRS spectrum coming to market. The wireless services on CBRS networks may be viewed as "cable wireless" extension beyond the 5GHz band, and possibly as another data offload network for the cable operators' MVNO business.

For the cable operators, CBRS offers lower unit cost. For cable operators who can leverage owned fiber and DOCSIS networks for backhaul, the unit cost per GB can be almost one-third that of an operator leasing backhaul. In the end, wireless service is about transporting bits. Having owned network infrastructure for backhaul provides tremendous advantages in wireless services as well, especially when one can leverage less expensive unlicensed or shared spectrum.



Notes: 1) Assume that a cable operator would use own fiber or DOCSIS as backhaul;
2) Although a cable operator can theoretically deploy licensed small cells, upfront spectrum cost can be too prohibitive

Source: Mobile Experts

Figure 11. Cable Operator's Unit Cost of LAA vs. CBRS vs. Wi-Fi

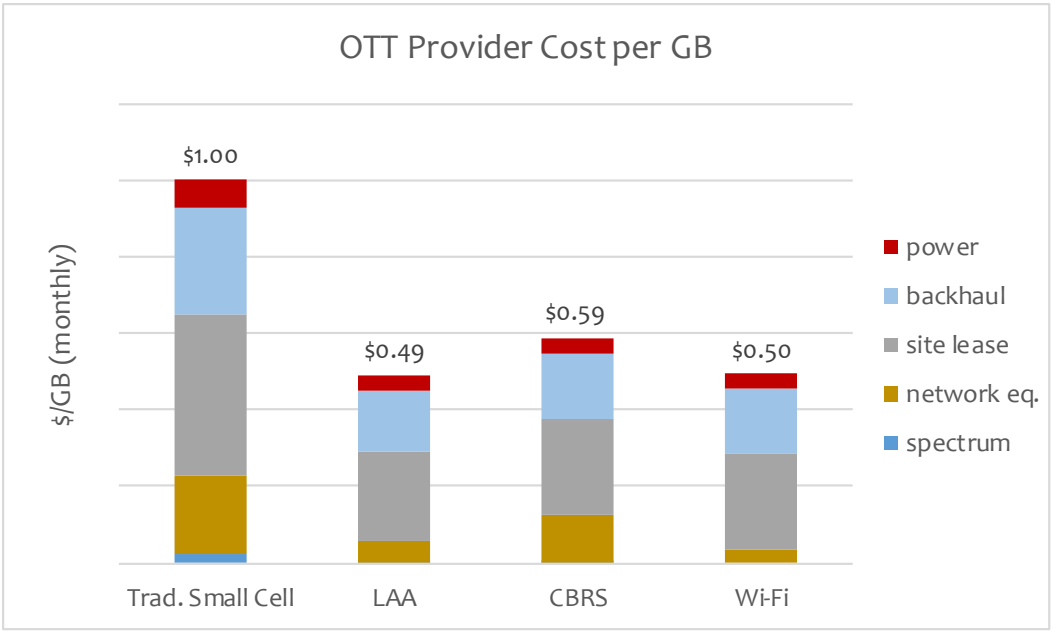
The cable operators view public Wi-Fi hotspots as a strategic asset in their pursuit of mobile wireless entry. In pursuit of this strategy, they appear inclined to continue making investments in public hotspots through outdoor deployments and public access via Wi-Fi enabled broadband CPEs. Using strategically placed hotspots as a foundation of their wireless footprint, cable operators have been experimenting with various business models ranging from wholesale access to retail wireless services. Comcast's (and soon Charter's) MVNO business launch portends more expeditious LTE-based network deployments by the cable operators in our view. As an MVNO, they are incentivized to offload subscribers' traffic onto owned infrastructure to lessen the MVNO rent fees to a host mobile operator. It is possible for the cable operators to pursue LAA and LWA (through license acquisition or lease), but Mobile Experts believes that CBRS is a more likely path for the cable operators for now as it offers less onerous upfront spectrum cost to build up a LTE network.

Over-the-Top / Neutral Host Service Provider Perspective and Choices

Over-the-top (OTT) Wi-Fi operators like Boingo have been providing public wireless service over the unlicensed bands for many years. These providers have focused on strategic public venues like airports to establish a wireless footprint using Wi-Fi. They have typically charged for roaming access to mobile operators or other service providers and per-use fee to retail customers. A good example of a wholesale business model is the Wi-Fi roaming agreement that Boingo has established with Sprint. Under this agreement, Sprint customers can automatically roam onto Boingo's Wi-Fi networks at major US airports and use the networks as if they are on Sprint's network coverage. With Hotspot 2.0 profiles pre-installed on Sprint

phones, Sprint customers can seamlessly access Boingo's Wi-Fi network without the typical Wi-Fi login process. While the wholesale Wi-Fi access business can bring a meaningful revenue contribution, it has been tough to convince certain mobile operators to use Wi-Fi for mobile services.

Although its unit cost is slightly higher than Wi-Fi, mainly due to the SAS burdened cost embedded in the network equipment cost, CBRS offers an inexpensive means to build up LTE network. Without high upfront costs for spectrum, OTT and neutral host providers can selectively build out CBRS network to serve specific market needs. For example, a neutral host provider can build in-building wireless system based on CBRS small cells to offer LTE network services to enterprises directly or through mobile operators. Assuming that future smartphones distributed through mobile operator channels support CBRS, OTT service providers can potentially offer much more cost-effective in-building wireless solutions than traditional DAS solutions.



Notes: 1) Assume WiGig PTP 60GHz radio deployment for small cell backhaul to lessen the backhaul cost;
2) Assume that WiGig PTP radio gear has a 5-year lifespan;
3) Although an OTT operator can theoretically deploy licensed small cells, upfront spectrum cost is too prohibitive to be realistic (for reference only)

Source: Mobile Experts

Figure 12. OTT Operator's Unit Cost of LAA vs. CBRS vs. Wi-Fi

Fixed vs. Mobile Competition and Unlicensed Use

As mobile and fixed operators pursue their respective wireless network strategies, it is interesting to contrast the differing motivations. With broad coverage in place with low-band LTE deployments, mobile operators are pursuing small cell densification projects to increase capacity in strategic hotspot locations. Meanwhile, fixed or cable operators are

looking to "stitch" together various public hotspots that constitute their wireless network to provide a broader coverage. As the competition for consumer dollars for fixed and mobile broadband services increases, the operators from both camps appear to be heading towards intermodal competition, indirectly competing for the unlicensed spectrum bands in those same strategic locations where consumers are likely to access broadband services.

Mobile operators are looking to harness the unlicensed bands using LTE-based technologies especially LTE-U/LAA to take advantage of existing LTE core infrastructure and operational simplicity. Cable operators have largely relied on inexpensive Wi-Fi infrastructure for their wireless access networks. If the cable operators look to pursue LTE-based technologies like the mobile operators, they will need to make investments in LTE core networks, which may not be trivial, but achievable – and likely necessary as they pursue mobile service opportunities.

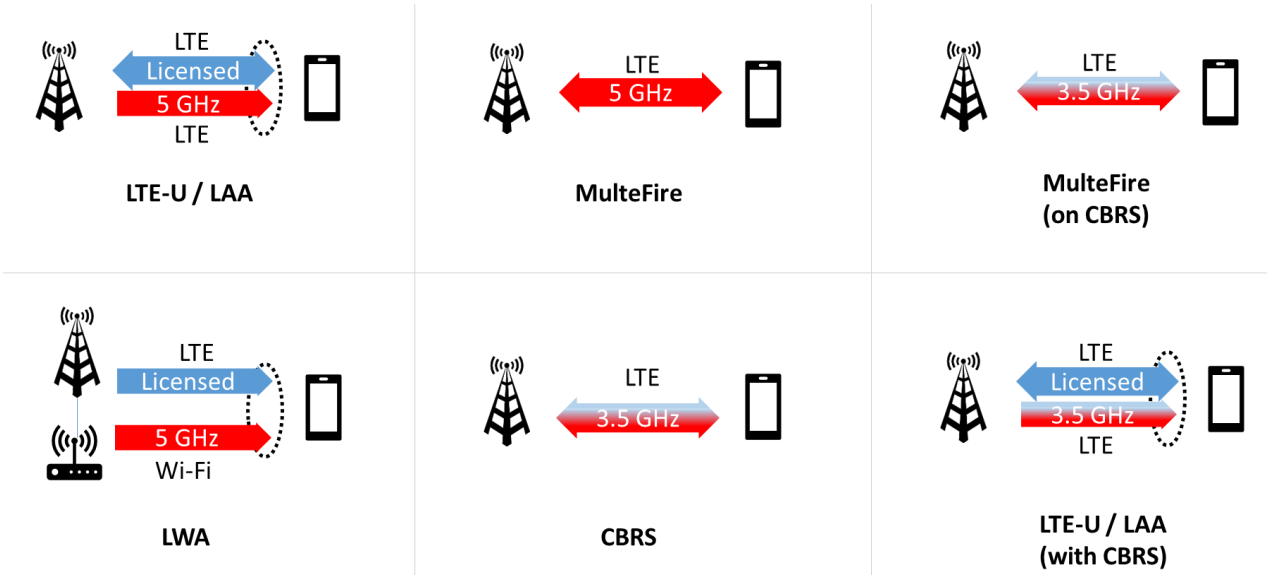
The major cable operators in the USA have now entered the mobile business via MVNO. In kind, the major mobile operators are trialing 5G fixed wireless services as a possible response. As both cable and mobile operators increase their competitive intensity across respective core markets, the unlicensed band is expected to become an important battleground in the fixed vs. mobile competition. Spectrum is a fundamental commodity in wireless business irrespective of whether it is licensed, unlicensed or shared. A key question for them is whether the unlicensed band can be utilized in a manner that provides traditional quality of service that end users expect.

4 TECHNOLOGY OPTIONS

Operators looking to provide carrier-grade service over unlicensed and shared bands have several LTE-based alternatives beyond Wi-Fi. While the Wi-Fi ecosystem continues to advance 802.11 technology features such as 802.11ax to alleviate network congestion, the fundamental problem with Wi-Fi is not getting resolved. Wi-Fi continues to have the same contention between users, which results in unpredictable loss of performance. Faster speed is not the issue with Wi-Fi: it's the reliability of Wi-Fi that limits its popularity.

LTE proponents are also driving forward technology advancements and ecosystem development for LTE use in the unlicensed and shared spectrum bands. Over the course of the past two years, several key LTE-based technology ecosystems have evolved, including:

1) *LTE-Unlicensed (LTE-U)* – a pre-Release 13 technology developed by Qualcomm, Ericsson, and other key operator stakeholders, namely T-Mobile and Verizon, to aggregate unlicensed carriers with an anchor carrier in the licensed band;
2) *License-Assisted Access (LAA)* – a 3GPP Release 13 standard that essentially formalizes LTE-U (downlink carrier aggregation). Unlike LTE-U, fair coexistence with Wi-Fi in the unlicensed spectrum is handled by listen-before-talk (LBT) capability to ensure that channels are clear before transmission;
3) *LTE-WiFi Aggregation (LWA)* -- a 3GPP Release 13 standard that aggregates channel carriers at PDCP layer for downlink. LTE eNodeB base station decides which bearers (Wi-Fi and LTE) to use;
4) *MulteFire* -- running standalone LTE on unlicensed (or shared) spectrum without aggregating unlicensed carrier with a licensed carrier
5) *Citizen Broadband Radio Service (CBRS)* – a three-tier licensing regime that allows operators to use 150MHz of the 3.5 GHz band in the U.S. on a shared basis. The CBRS channels can be aggregated along with a licensed anchor in LAA fashion or can run LTE-TDD on a standalone basis



Notes: 1) Blue arrow represents licensed spectrum; Red represents unlicensed spectrum; Blue/Red gradient represents shared spectrum;
2) Directions in arrows represent downlink or both downlink and uplink operation on specific spectrum type;
3) Dotted ellipse represents that licensed/unlicensed/shared spectrum carriers are aggregated at the UE client device;
4) "Standalone" LTE via MulteFire can run on 5 GHz unlicensed spectrum as well as shared CBRS spectrum on PAL or GAA basis;
5) Multiple carriers on shared CBRS spectrum can be aggregated with licensed anchor carrier in LTE-U/LAA.

Source: Mobile Experts

Figure 13. LTE-based Unlicensed and Shared Spectrum Technology Options

The unlicensed LTE technologies that require license-assisted access (LTE-U / LAA) or LTE base station and Wi-Fi access point coordination (LWA) are naturally fit for mobile operators who own LTE infrastructure and licensed spectrum. The other options including CBRS, MulteFire and Wi-Fi provide non-mobile operators to take advantage of the unlicensed or shared spectrum bands.

	LTE-U / LAA	LWA	CBRS*	MulteFire	Wi-Fi
Air Technology	3GPP LTE	3GPP LTE	3GPP LTE	3GPP LTE	IEEE 802.11
Spectrum	5 / 3.5 GHz	5 GHz	3.5 GHz	5 / 3.5 GHz	2.4 / 5 / 60 GHz
(Carrier) Target	Mobile	Mobile	Cable, Mobile, Wireless ISP, Neutral Host, Enterprise	Cable, OTT, Neutral Host, Enterprise	Any one

(*) Note: Although CBRS denotes shared spectrum bands and licensing rules around using the band on a shared basis, "CBRS" is loosely referred to as a shared spectrum technology in this report.

Source: Mobile Experts

Figure 14. Unlicensed and Shared Spectrum Technology Options

802.11ac and 802.11ax (Wi-Fi Connectivity on 2.4 and 5 GHz)

The next-generation Wi-Fi broadband technology, 802.11ax, is sometimes referred to as *high-efficiency wireless* (HEW). As the name implies, one of the main goals of 802.11ax is to improve the average user throughput in dense environments, which is a key deficiency often cited in increasingly dense Wi-Fi deployments. In major urban centers, a Wi-Fi client can sometimes see 30-40 SSIDs in major urban environments. Despite multi-gigabit peak speeds often touted, average user experience is often frustratingly slow in public Wi-Fi environments such as airports. In addition to the main objective of alleviating network congestion, 802.11ax is expected to support higher data rates and improved channel access, with significant changes in the physical layer while maintaining a backward compatibility with previous 802.11n/ac devices.

Some of the key differences between 802.11ac and 802.11ax are highlighted below.

	802.11ac	802.11ax
Frequency bands	5GHz	2.4GHz and 5GHz
Channel sizes	20, 40, 80, 160 MHz	20, 40, 80, 160 MHz
FFT sizes	64, 128, 256, 512	256, 512, 1024, 2048 (four times larger)
Subcarrier spacing	312.5KHz	78.125 kHz (four times narrower)
OFDM symbol duration	3.2 usec + 0.8/0.4 usec cyclic prefix	12.8 usec + 0.8/1.6/3.2 usec cyclic prefix (four times longer)
Modulation (highest)	256 QAM	1024 QAM
Data rates (peak)	433 Mbps (80MHz channel bandwidth, 1 spatial stream)	600 Mbps (80MHz channel bandwidth, 1 spatial stream)
	6.9 Gbps (160MHz channel bandwidth, 8 spatial streams)	9.6 Gbps (160MHz channel bandwidth, 8 spatial streams)

Source: Mobile Experts, National Instruments

Figure 15. Comparison of 802.11ac vs. 802.11ax

As noted above, 802.11ax operates in both 2.4 and 5GHz bands. More importantly, it significantly increases the number of subcarriers while preserving the existing channel

bandwidth. Larger OFDM FFT sizes, narrower subcarrier spacing, and longer symbol time, in aggregate, improves robustness and efficiency while keeping the data rates the same as 802.11ac. In fact, with a higher modulation support for 1024 QAM, the 802.11ax provides a higher maximum data rate. More importantly though, it provides higher efficiency in multipath fading environments. With the higher number of subcarriers, the 802.11ax can more efficiently support simultaneous client devices by effectively divvying up the frequency.

Like 802.11ac, 802.11ax devices use explicit beamforming to direct data packets simultaneously to multiple users who are spatially separated. While the 802.11ac only defined MU-MIMO on the downlink, the 802.11ax standard defines uplink multiuser mode as well in which simultaneous data transmission from multiple client devices to an access point is possible. Another key addition of the 802.11ax standard is that it has defined two different ways of multiplexing users: Multiuser MIMO (MU-MIMO) and Multiuser Orthogonal Frequency Division Multiple Access (MU-OFDMA). In essence, 802.11ax borrows the underlying OFDMA technology used in LTE base stations to centrally manage multiple client devices, thus enabling more efficient access to a radio channel.

MU-MIMO operation in 802.11ax is essentially the same as the 802.11ac, in which an access point calculates a channel matrix for each user and steer simultaneous beams to different users with each beam containing specific packets for the intended client user. In 802.11ax, a maximum number of MU-MIMO transmissions has been increased from four to eight. For the uplink MU-MIMO, the access point initiates a simultaneous uplink transmission from each of the client devices by a trigger frame. In the case of multiple client devices responding in unison, the access point applies the channel matrix to the received beams and separates the information from each uplink beams.

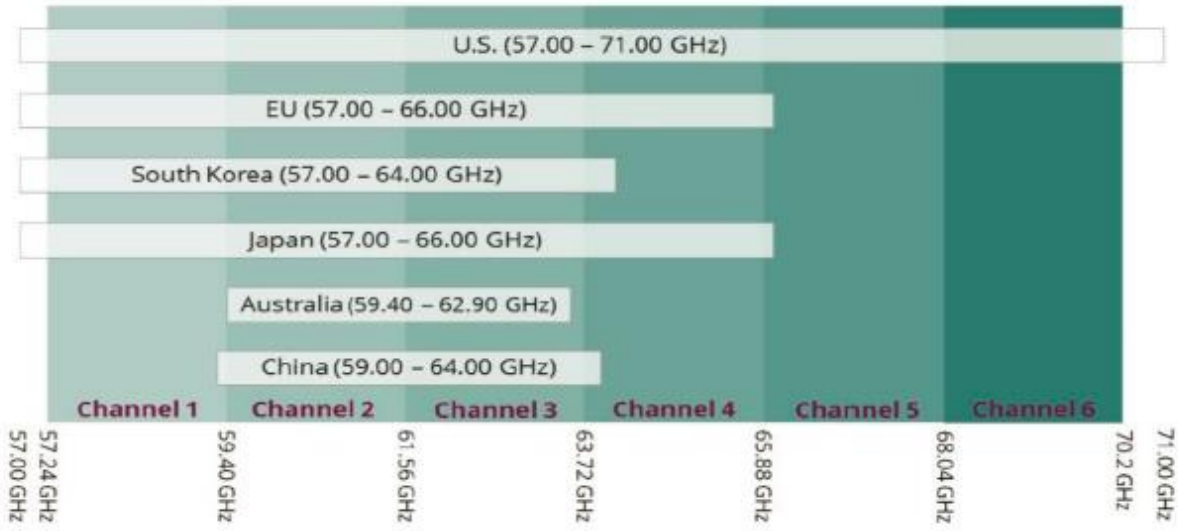
In MU-OFDMA operation, specific sets of subcarriers can be allocated to different users over time. In fact, this is the same scheme that LTE uses in allocation of physical resource blocks for multiple users. Borrowing a similar LTE terminology, the 802.11ax defines the smallest subchannel as a Resource Unit (RU), with a minimum size of 26 subcarriers. As noted in the figure below, an access point can allocate the entire (20/40/80/160 MHz) channel to only one user at a time as is currently done in 802.11ac, or it can "chop up" the frequency (in RU) and allocate specific sets of RUs to different users over time.

Also, the resource scheduling in the uplink increases efficiency by moving away from contention-based resource allocation found in 802.11ac to scheduling approach (like LTE). With a combination of downlink and uplink MU-MIMO and MU-OFDMA, the 802.11ax is expected to support four times the average user throughput. With combinations of these techniques and higher physical data rates, 802.11ax is expected to improve user throughput and extend coverage with higher 8x8 MIMO, especially in dense environments, which has been an Achilles' Heel for Wi-Fi relative to LTE. Note that the MU-OFDMA and resource scheduling will improve contention between clients that share an access point, but not for users on different access points.

802.11ad and 802.11ay (WiGig Connectivity on 60 GHz)

The 60 GHz unlicensed technology widely known as WiGig has been around for many years. After the WiGig Alliance merged into the Wi-Fi Alliance back in early 2013, 802.11ad WiGig technology has been positioned as a "multi-gigabit Wi-Fi" technology for short-range applications such as wireless connectivity for VR headsets, HDMI/USB replacement, and so on. In the carrier space, 60 GHz WiGig solutions are sometimes found in short-range wireless backhaul applications.

A key benefit of WiGig are the ultrawide channels – 2.16 GHz channel spacing! A whole lot can be transmitted in that amount of spectrum. Due to the physical limits of RF propagation at the 60 GHz band, a range is fairly short – typically 200 meters in point-to-point wireless backhaul applications.



Source: Peraso

Figure 16. WiGig (60 GHz) Spectrum

802.11ay is the next-generation 60 GHz WiGig technology that further extends the transmission speed and range. A draft 1.0 of the 802.11ay specification is expected to be released in the second half of 2017. According to the draft specification, the standard proposes to support 20-30 Gbps transmission rate and extend the range to 300-500 meters. These improvements are expected to be achieved through:

1) Up to 4 channel bonding (each 802.11ad channel uses a maximum of 2.16 GHz bandwidth), yielding a maximum bandwidth of 8.64 GHz
2) MIMO with a maximum of 4 spatial streams (a link rate per stream is 44 Gbps; thus with 4 streams, this can go up to 176 Gbps)
3) High-order modulation scheme, possibly up to 256 QAM

With the tremendous amount of spectrum available in the 60 GHz unlicensed spectrum, 802.11ad and 802.11ay solutions should find a home in many consumer and enterprise applications. For the carrier space however, it will likely be used only for the wireless backhaul application in dense urban environments.

LTE-U and LAA (on 2.4 GHz and 5 GHz)

LTE-Unlicensed (LTE-U) and its 3GPP Release 13 standardized version, License Assisted Access (LAA) are built upon the carrier aggregation framework adopted in LTE Advanced (Release 10-13). Carrier aggregation combines more than one channel within the same band or with another band, effectively increasing the overall bandwidth available to a user equipment, thereby increasing bitrate. The LTE-U proposed by leading mobile industry players seeks to aggregate the unlicensed band as a secondary cell for downlink while the primary cell connection reserved for control signaling and uplink is anchored to a licensed band. Due to regulatory differences, LTE-U supplemental downlink can be deployed in the US and Korea with the CSAT method5, while Europe and Japan requires the "list before talk" (LBT) feature. Standardized LAA is expected to bring global scale to the LTE-U/LAA ecosystem, but the mobile operators--especially those in the US, Verizon and T-Mobile--have been very vocal about bringing LTE-U solutions to the market by end of 2016.

One of the key debates around LTE-U/LAA has been the idea of "fair" coexistence with Wi-Fi in the 5GHz unlicensed band. Wi-Fi proponents, such as Google and cable operators who have largely relied on Wi-Fi to this point, for their wireless "plays"6 have raised coexistence concerns.7 The US Federal Communications Commission (FCC) has largely stayed on the sideline, asking the industry to sort things out. While the Wi-Fi Alliance (WFA) works towards a coexistence test plan by September 2016, LTE-U proponents are actively conducting field trials.8 Based on slower than expected completion of the coexistence test plan, LTE-U commercial deployments aren't likely to begin until start of 2017. The market time advantage of LTE-U may simply go away if the coexistence verification and FCC equipment certification approval prolongs much further. In the end however, LTE use in the unlicensed bands either as LTE-U or LAA will eventually happen as mobile operators push to

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[5] Carrier Sense Adaptive Transmission (CSAT) is a dynamic duty cycling method to turn on/off the LTE-U transmission based on transmission measurements from Wi-Fi access points.

[6] Google Fi MVNO service whereby mobile data use is defaulted to Wi-Fi and falls back to T-Mobile or Sprint cellular network when Wi-Fi access is not available. Meanwhile, cable operators have been leveraging premise and public Wi-Fi to wireless extend their fixed broadband services.

[7] Key concerns raised by Wi-Fi proponents include the ability of deployed Wi-Fi devices to detect a free channel, and the aggressiveness of LTE-U/LAA devices to detect and avoid conflict with (Wi-Fi) "neighbors" through appropriate settings of energy detect threshold and backoff parameters. Broadcom has proposed -82 dBm energy detect threshold consistent with Wi-Fi preamble detect levels. According to Broadcom, 50% of Wi-Fi links are below -80 dBm.

[8] Verizon is conducting LTE-U field trials in OKC and Raleigh, NC. Meanwhile, Ericsson is reporting trials and coexistence verification testing globally.

harness unlicensed spectrum through handset upgrades and indoor and outdoor small cell deployments with LTE-U/LAA support embedded.

LWA and LWIP

In addition to the LAA specification, 3GPP Release 13 also defined a couple of WLAN interworking features to harness unlicensed spectrum use through optimally integrating Wi-Fi with LTE access network, namely: LTE WLAN Aggregation (LWA) and LTE WLAN Radio Level Integration with IPSec Tunnel (LWIP). Both LWA and LWIP essentially aggregate or switch data traffic over LTE and Wi-Fi airlinks at radio access network level. It is expected that LWA and LWIP would provide load balancing benefit between LTE and Wi-Fi networks through aggregation or switching. In effect, end users would experience a capacity boost from utilizing Wi-Fi network as if they were using LTE.

In LWA, eNodeB base station schedules PDCP packets and transmit some over LTE via LWA-aware eNodeB and others over Wi-Fi via Wi-Fi access points. The LTE transmission over Wi-Fi link is encapsulated in Wi-Fi frames. In LWA, there is no coexistence issue as unlicensed band use is strictly confined to Wi-Fi while licensed band use is done over LTE. All received packets, via LTE and Wi-Fi links, are then aggregated at the PDCP layer at the client UE device. While the whole LTE-WiFi coexistence issue can be avoided with this architecture, LWA imposes changes to core networking and upgrades to both LTE eNodeB base station, Wi-Fi access point, and UE client devices. For these reasons, Mobile Experts believes that LWA deployments will likely be limited to mobile operators who have mature Wi-Fi networks that they intend to leverage over a longer term.

LWIP is similar to LWA but performs LTE and Wi-Fi traffic aggregation and switching at the IP layer, just above PDCP. Similar to Wi-Fi Calling architecture, LWIP uses IPSec tunnel between eNodeB base station and client UE devices. The IPSec tunnel is terminated in the LWIP Security Gateway (LWIP-SeGW) integrated in the LTE eNodeB base station. While it is designed for faster time-to-market by requiring no changes to existing Wi-Fi infrastructure, and supporting both downlink and uplink data transmissions, LWIP imposes burdensome core network changes (i.e., LWIP SeGW integrated in LTE eNodeB base stations) and can impose significant control signaling traffic between millions of UE client devices and SeGW eNodeB base stations. For these reasons, Mobile Experts believes that mobile operators will not likely adopt LWIP.

As outlined in the summary comparison table below, one of the key advantages of LWIP over LWA is that it can work with legacy Wi-Fi network infrastructure while LWA requires updates to Wi-Fi network infrastructure.

	eNB control	WLAN measurements	Offload granularity	WLAN traffic direction	Feedback/flow control	Fast WLAN authentication	WLAN infrastructure impact	New network nodes
LWA	Yes	Yes	Split bearer	DL only	Yes	Yes[2]	Yes[4]	WT
LWIP	Yes	Yes	Bearer[1]	DL + UL	No	No[3]	No	LWIP-SeGW

1. When a bearer is configured to use IPsec, LTE DRB configuration remains, however eNB is not expected to send packets on LTE and IPsec simultaneously, as LWIP does not support re-ordering
2. After connecting to WLAN, LWA UE only performs 4-way handshake (if network uses the eNB based authentication)
3. After connecting to WLAN, LWIP UE performs WLAN native 802.1x EAP/AKA authentication, IP address acquisition and IPsec tunnel establishment
4. Impact due to eNB based authentication mechanism, if used by network. Optional UE feedback mechanisms (as opposed to network feedback) allow to limit WLAN infrastructure impact of LWA

Source: 3GPP

Figure 17. LWA vs. LWIP Comparison

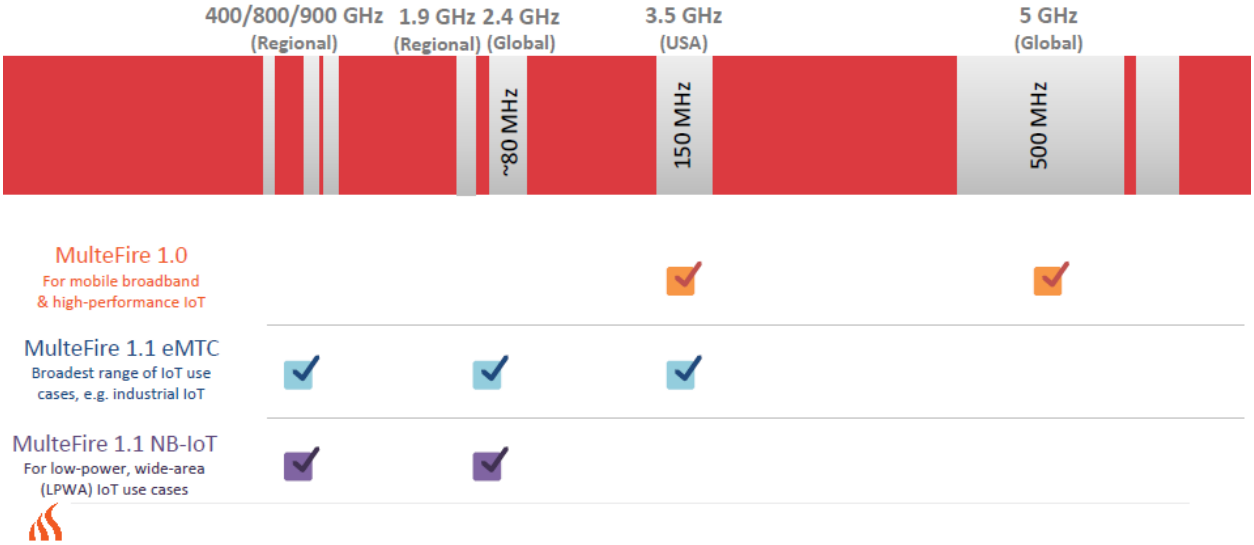
MulteFire (on 3.5 GHz, 5 GHz, and Beyond)

Qualcomm, Nokia, Ericsson, and Intel have formed the MulteFire Alliance to push for the unlicensed LTE technology that can be leveraged without a licensed spectrum anchor. In essence, MulteFire is an incarnation of LAA for those operators who do not have licensed spectrum, i.e., non-mobile operators. Unlike LAA which precludes use by those who do not have licensed spectrum, MulteFire proposes to carry both control plane and data plane traffic entirely over unlicensed band in a full TDD mode. Thus, it can be leveraged by enterprises, venue owners, and fixed providers. It is still unclear today how much the efficiency gain of LAA (over Wi-Fi) can be maintained in the MulteFire format---especially in light of the fact that 802.11ax products touting 4x average user throughput improvement would likely compete against MulteFire products in the marketspace.[9] In theory, the LTE-U ecosystem can be broadened to fixed operators or enterprises who may be looking to take advantage of LTE features such as seamless authentication and mobility, without incurring the high cost of licensed spectrum.

In practice, however, the adoption of MulteFire by the key target audiences, enterprises and operators, remains unclear. Enterprises have a large installed base of Wi-Fi systems and client devices. Though the neutral host and multi-operator aspects of MulteFire are clear demand drivers of this segment, whether the MulteFire ecosystem can achieve competitive equipment pricing and scale of Wi-Fi remains a big unknown.

[9] According to Qualcomm's MulteFire presentation dated May 24, 2016, MulteFire is expected to offer ~2x capacity gain over Wi-Fi (802.11ac). IEEE 802.11ax stated goal is to improve the average user throughput by 4x.

One likely area of market adoption of MulteFire may be in 3.5GHz CBRS deployments. Traditional mobile and Wi-Fi infrastructure vendors such as Nokia, Ericsson, Cisco, and Ruckus have joined the MulteFire Alliance and working to define an industry standard around the standalone LTE technology that can be applied in the unlicensed and shared spectrum bands. While we remain skeptical of its viability in the 5GHz band, we believe the benefits of MulteFire, namely neutral host support, private LTE broadband, and fair coexistence with other technologies may be especially compelling in the "new" 3.5GHz CBRS band use. In addition, it may provide a suitable solution for industrial IoT applications that require more deterministic service quality -- guarantees of performance will be more achievable with LTE than with Wi-Fi. As outlined in MulteFire roadmap below, the ecosystem is already thinking towards the IoT applications for standalone LTE in unlicensed bands.

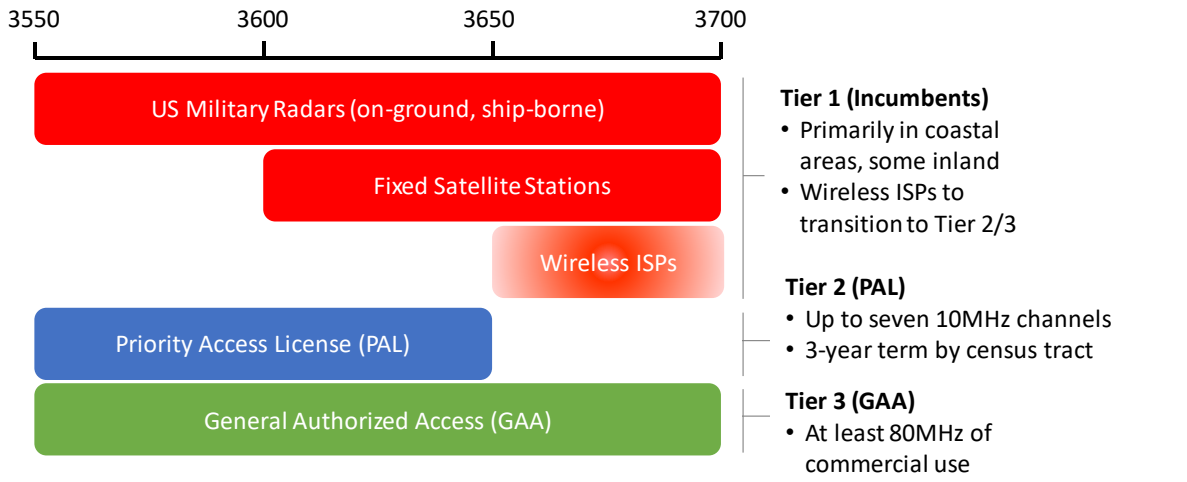


Source: MulteFire Alliance

Figure 18. MulteFire Roadmap Targets Mobile Broadband and IoT

CBRS (on 3.5 GHz)

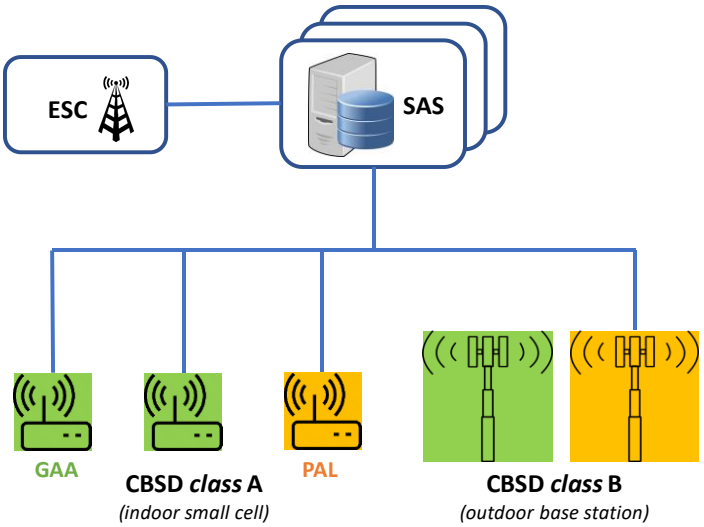
In 2015, the U.S. Federal Communications Commission (FCC) formally established *Citizen Broadband Radio Service* (CBRS) for shared commercial use of the 3.5 GHz (3550-3700 MHz) band with the incumbent military radars and fixed satellite stations. For the first time, dynamic spectrum sharing rules have been defined to make additional spectrum available for flexible wireless broadband use while ensuring interference protection and uninterrupted use by the incumbent users. Under the plan, a three-tier sharing paradigm coordinates spectrum access among the incumbent military radars and satellite ground stations and new commercial users. The three tiers are: *Incumbent*, *Priority Access License* (PAL), and *General Authorized Access* (GAA) users.



Source: Mobile Experts

Figure 19. CBRS Three-Tier (Shared Spectrum) Licensing Structure

A key element of the CBRS spectrum sharing architecture is the *Spectrum Access System* (SAS). A SAS maintains a database of all CBRS base stations, formally referred to as *Citizens Broadband Radio Service Devices* (CBSDs), including their tier status, geographical location, and other pertinent information to coordinate channel assignments and manage potential interferences. To mitigate possible interference to tier 1 military radar systems, environmental sensors known as the *Environmental Sensing Capability* (ESC) are deployed in strategic locations near naval stations, mostly along coastal regions, to detect incumbent activities. When incumbent use is detected, the ESC alerts the SAS, which then directs CBSDs utilizing impacted CBRS channels in that area to move over to other channels. The cloud-based SAS enforces the three-tier spectrum sharing mechanism based on FCC rules via centralized, dynamic coordination of spectrum channel assignments across all CBRS base stations in a region.



Source: Mobile Experts

Figure 20. CBRS Functional Overview

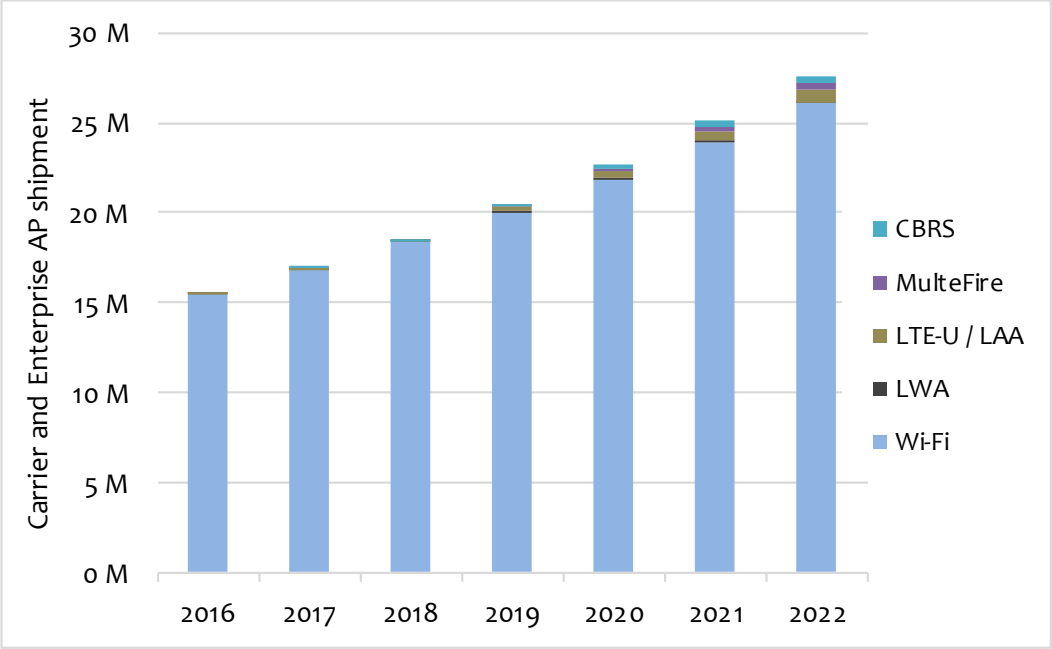
The CBRS rulemaking defines two classes of base stations: *class A* and *class B*. A class A base station can be thought of as indoor or low power outdoor small cells with a maximum conducted power of 24 dBm (per 10 MHz) and maximum EIRP of 30 dBm (1 watt). This type of small cell is similar to "enterprise-class" small cells in the marketplace with 250mW transmit power with a typical 2 dBi omni antenna or up to 6 dBi directional antenna. Meanwhile, a class B base station is meant for outdoor use with a maximum EIRP of 47 dBm (50 watts). With a very high-gain antenna, outdoor CBRS base station can potentially be used for fixed wireless purposes. While indoor and outdoor base stations can be assigned to either GAA or PAL, we expect to see more indoor GAA deployments until ESC certification and PAL auctions get finalized.

The CBRS ecosystem is progressing along with FCC certification of SAS expected by end of 2017. While there is some uncertainty around possible CBRS rule changes around larger spectrum "parcel" size and licensing term extension from three to ten,[10] major operators are pushing ahead with CBRS radio deployments in 2018. The interests around CBRS deployment have heightened over the course of 2017. While the possible rule changes may impact a longer-term prospect of CBRS market, Mobile Experts believes that near-term deployment plans will push ahead as CBRS network deployments will likely aid cable operators' strategic leverage with mobile operators in MVNO negotiations and/or possible M&A discussions.

[10] CTIA and T-Mobile separately requested CBRS rule changes to FCC: http://www.fiercewireless.com/wireless/t-mobile-joins-ctia-pushing-fcc-to-reform-rules-for-3-5-ghz

5 LTE-U AND CARRIER WI-FI OUTLOOK

Unlicensed spectrum bands have historically been the realm of Wi-Fi technologies, primarily for enterprise wireless local area networking (WLAN) services. With the popularity of smartphones, especially the iPhone, carriers began to leverage Wi-Fi infrastructure to take advantage of unlicensed spectrum for data offload to alleviate pressure on their mobile networks. With the growing ecosystem of LTE-based technologies coming to market, in addition to the new shared spectrum in the 3.5 GHz CBRS band, it is inevitable that LTE-based unlicensed technologies such as LTE-U/LAA, LWA, MulteFire, and CBRS will co-habit the unlicensed bands in both the Carrier and Enterprise markets.



Source: Mobile Experts

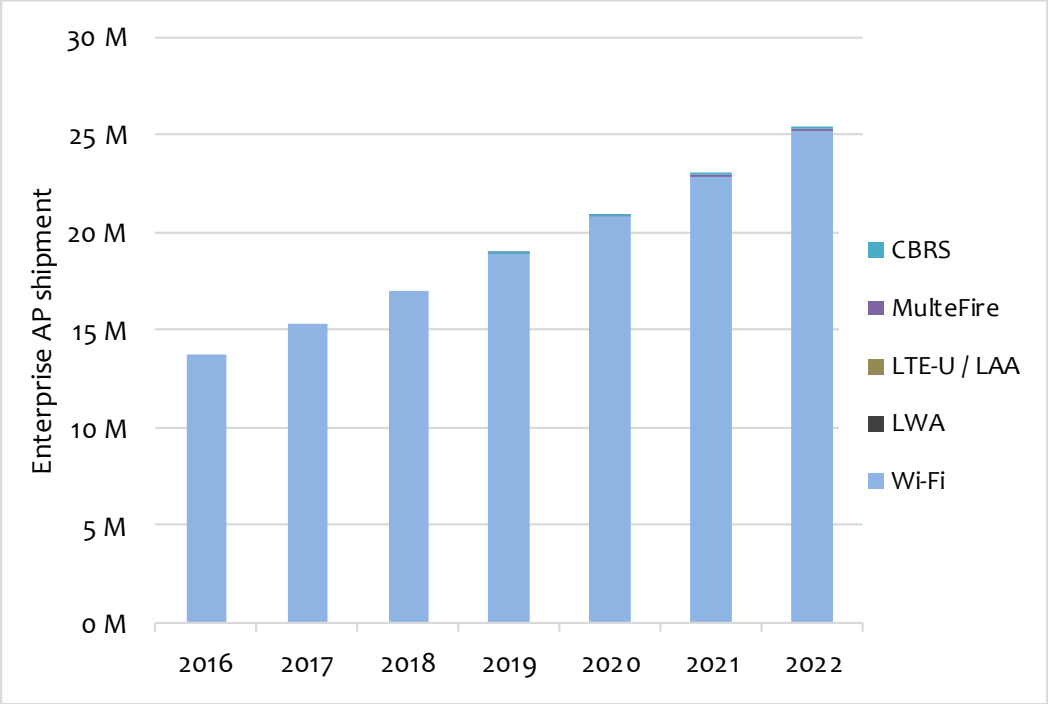
Chart 2: Carrier and Enterprise AP Shipment by Unlicensed Technology, 2016-2022

While the LTE-unlicensed technologies are expected to see explosive growth, the cumulative share of these technologies is expected to be only 6% of the overall Carrier and Enterprise Wi-Fi market in terms of annual equipment shipments at the end of the forecast period. A very large Enterprise WLAN market dwarfs the impact of LTE-based unlicensed access equipment market growth, in terms of unit shipments.

LTE-U Outlook in the Enterprise Segment

While the significant portion of the LTE-unlicensed growth is expected to come from the carrier adoption of LTE-based technologies in the unlicensed and shared spectrum bands, niche segments within the Enterprise wireless market, such as "private LTE" deployment scenarios and neutral host in-building wireless segments may see adoption of standalone LTE use via MulteFire in both unlicensed and shared spectrum bands. However, the overall

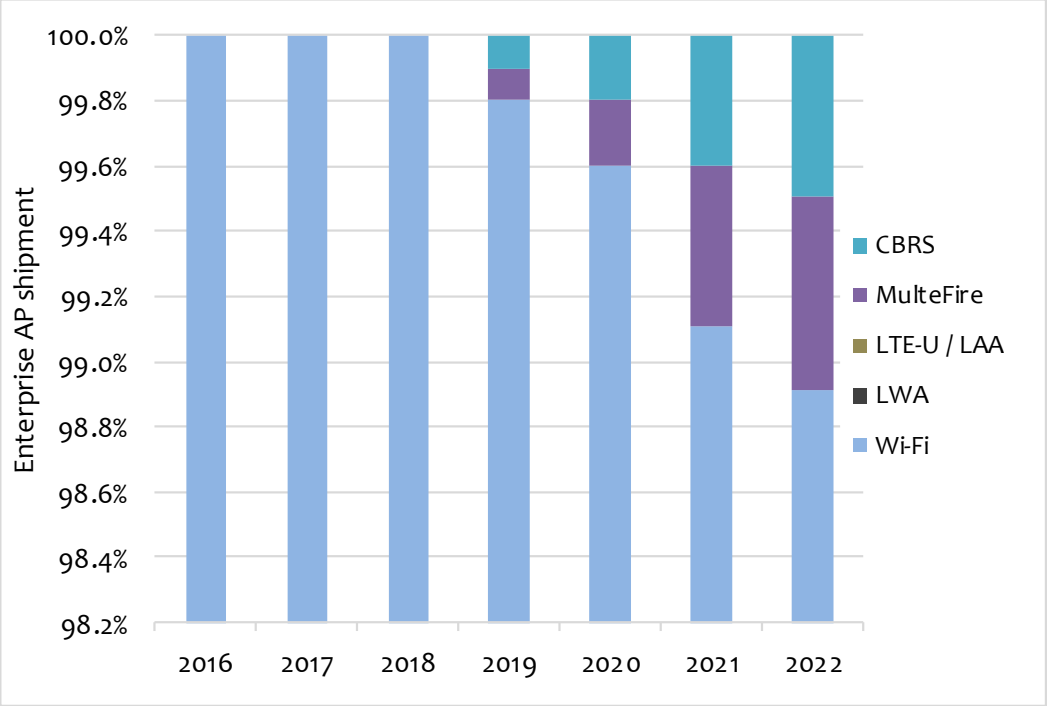
impact is expected to be minimal as the broadest use case for Enterprise WLAN will continue to leverage Wi-Fi technologies and its vast global ecosystem. With annual shipment of Wi-Fi chipsets in billions of units, the economies of scale of Wi-Fi reaches the broadest section of client devices and business use cases.



Source: Mobile Experts

Chart 3: Enterprise AP Shipment by Unlicensed Technology, 2016-2022

As shown below, the cumulative LTE-unlicensed technology share of the Enterprise wireless access market is forecasted to be insignificant - reaching just over 1% in 2022. While "standalone" LTE (without licensed anchor) via MulteFire may be ideally suited for certain enterprise use cases (e.g., private LTE or industrial IoT applications), in the context of much larger market, penetration of LTE-based unlicensed technologies is expected to be very small.



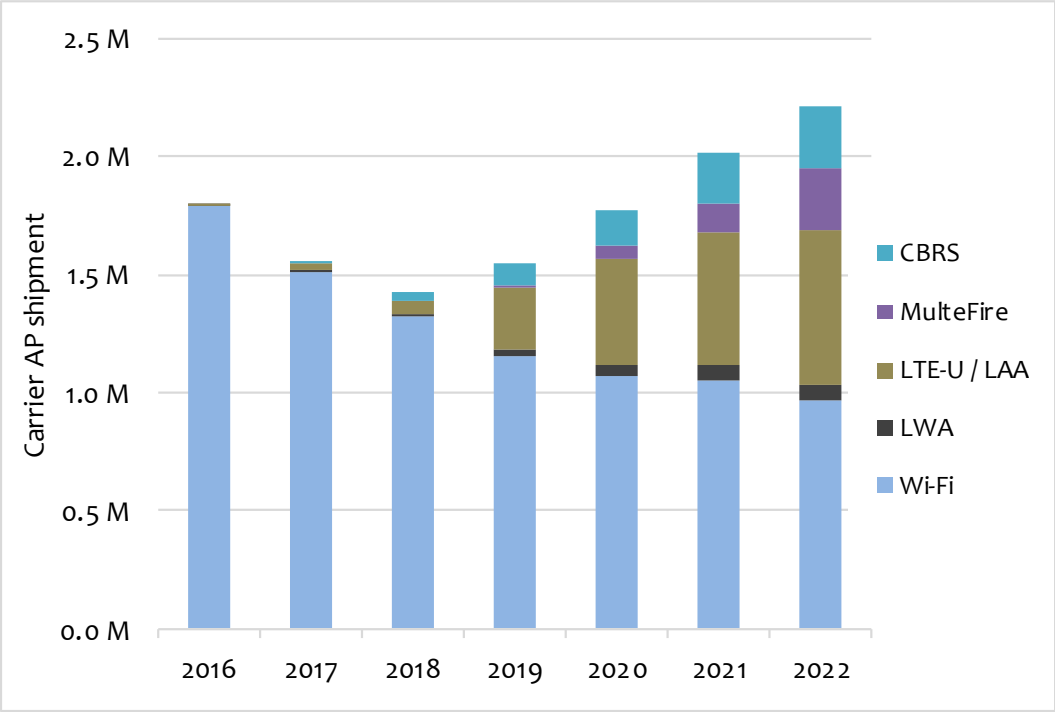
Source: Mobile Experts

Chart 4: Enterprise AP Unlicensed Technology Share, 2016-2022

LTE-U and Carrier Wi-Fi Outlook in the Carrier Segment

Peeling off the unit shipments of LTE-based unlicensed small cells and Wi-Fi access equipment for the Enterprise segment, the chart below showcases the unit shipments of LTE-based unlicensed small cells and Wi-Fi equipment for the Carrier segment. As the mobile industry recalibrates its unlicensed spectrum strategy away from Wi-Fi offload to Carrier Aggregation across licensed and unlicensed bands, Mobile Experts forecasts a slight dip in overall carrier access equipment shipments. The Carrier Wi-Fi market will decline as the LTE-based unlicensed ecosystem matures. As the LTE-U/LAA and CBRS ecosystems mature, we expect mobile operators to meaningfully roll out LTE-U/LAA small cells, along with higher category UE client devices to claim "Gigabit LTE" services leveraging LTE-Advanced Pro (3GPP Release 13 and beyond) features including 3-4 Carrier Aggregation, 256 QAM, and 4x4 MIMO to reach a peak throughput speed close to 1 Gbps downlink.

Mobile Experts believes that mobile operators will largely leverage the LTE-U/LAA technology to take advantage of the unlicensed and shared CBRS bands for Carrier Aggregation along with licensed spectrum bands to provide higher speed user throughputs (assuming that a handful of subscribers have latest Category 16 smartphones).

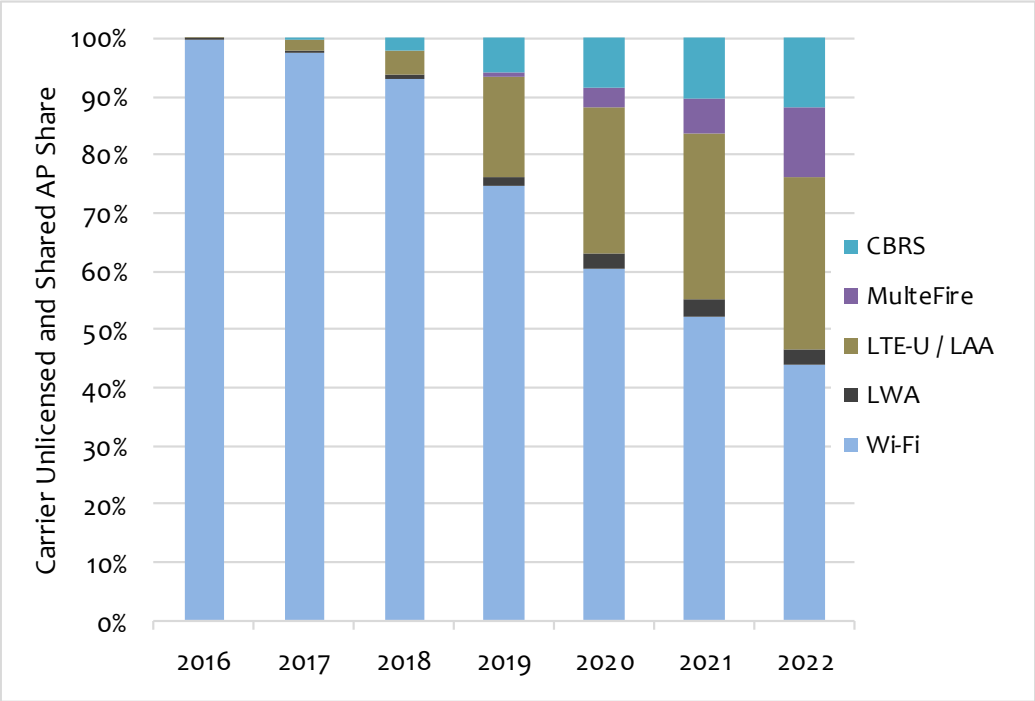


Source: Mobile Experts

Chart 5: Carrier AP Shipments by Unlicensed Technology, 2016-2022

With forecasted rapid adoption of LTE-based unlicensed technologies, the cumulative LTE-based unlicensed technology share of the overall Carrier wireless access market is forecasted to reach about 60% in 2022. With the initial LTE-U/LAA field trials bearing successful headline throughput numbers, Mobile Experts believes a significant worldwide deployment to occur in 2019 timeframe as initial live demos in Korea[11] and in the USA translate to global rollout of LTE-Advanced Pro networks supporting "Gigabit LTE" speeds (assuming subscribers have latest smartphones to take advantage of those single-user peak speeds).

[11] SK Telecom in Korea has already demonstrated five Carrier Aggregation, http://www.fiercewireless.com/wireless/samsung-sk-telecom-complete-3-5-ghz-5g-nr-trial



Source: Mobile Experts

Chart 6: Carrier AP Unlicensed Technology Share, 2016-2022

LTE-U and Carrier Wi-Fi Shipment by Service Provider

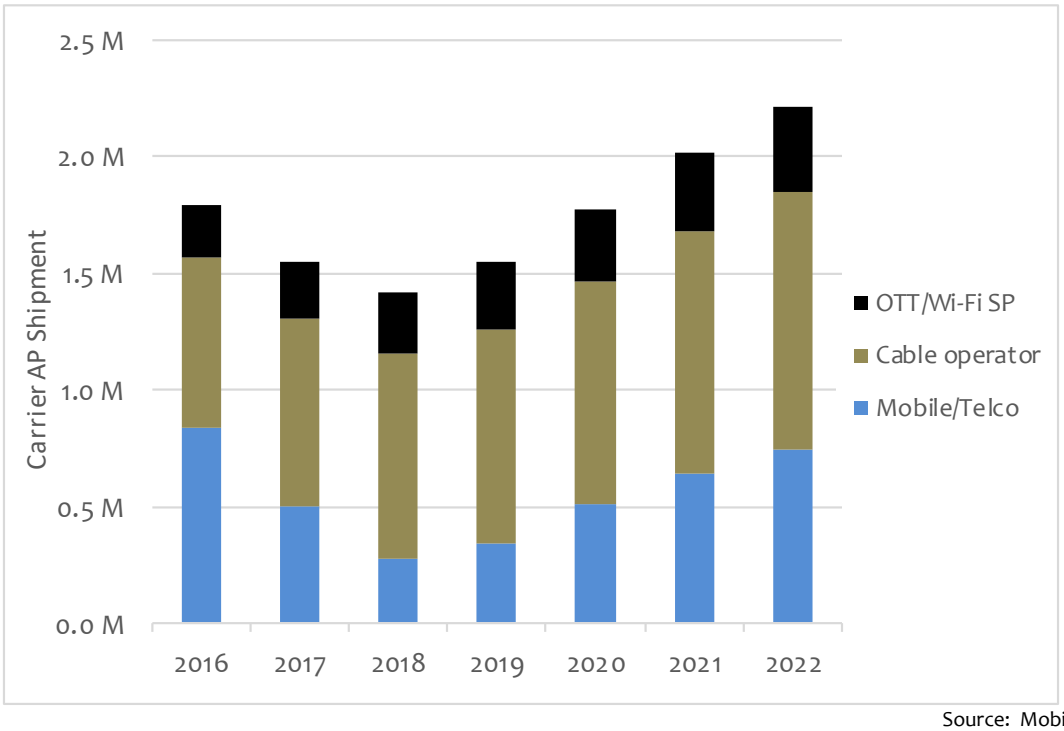
With a broader "menu" of technology choices and ecosystems to leverage unlicensed and shared spectrum bands, the different service providers will naturally gravitate towards specific technology choices based on market positioning, existing infrastructure and spectrum holdings (or lack thereof), and competitive dynamics. Mobile operators are preferring the LTE-U/LAA technology to seamlessly aggregate unlicensed spectrum to their licensed carriers to increase capacity while maintaining a level of control over service quality, which was missing in the traditional Wi-Fi offload method. Meanwhile, cable operators seem eager to leverage the new shared spectrum technology like CBRS to build up LTE network capacity alongside their Wi-Fi network. Like the cable operators, OTT and neutral host providers are showing strong interests in the new spectrum opportunities with CBRS.

Mobile operators now have multiple 3GPP standards-based LTE technologies for use in the unlicensed bands. With time-to-market advantages, LWA and LWIP appear to be one of the favored approaches for mobile operators with mature Wi-Fi footprint. For example, in last year's report, Mobile Experts expected China Mobile to pursue LWA more aggressively. So far, this has not panned out. Instead, we are seeing more market activity around LTE-U/LAA in markets where operators have limited licensed spectrum holdings. For traditional mobile operators with licensed spectrum assets, LTE-U/LAA offers an elegant and seamless means to aggregate unlicensed and shared spectrum based on common LTE technology, with

minimal impact to the existing core network. It provides a scalable way to incrementally deploy LTE-U/LAA small cells to increase capacity and boost user speeds where needed.

Meanwhile, Mobile Experts expects a majority of cable operator deployments to take the form of traditional carrier Wi-Fi access points with some contributions from MulteFire deployments in the later years in the forecast period. For cable operators with limited, or zero licensed spectrum holdings, MulteFire and CBRS radios are welcome technology additions in building LTE networks. Furthermore, based on recent competitive positioning of leading cable operators entering mobile wireless business,[12] we have factored in limited LAA and LWA adoption by cable operators starting in 2018. Although LWA theoretically can provide a path for cable operators to leverage their extensive Wi-Fi networks, we believe that this path requires additional complexity and dependency on LTE infrastructure and handsets that may be too big for cable operators to tackle on their own.

With limited capital expenditure budget and scale, we expect OTT and neutral host providers to largely look to traditional carrier Wi-Fi along with investments in CBRS radios for indoor wireless opportunities.



Source: Mobile Experts

Chart 7: LTE-U and Carrier Wi-Fi Access Equipment Shipment Forecast by Service Provider, 2016-2022

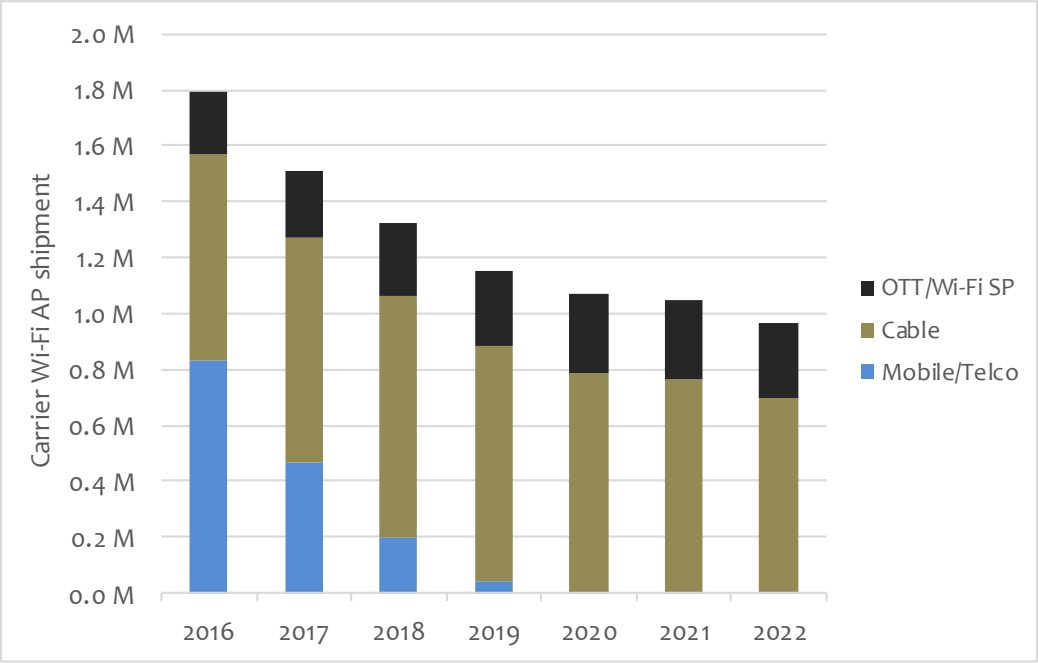
[12] Comcast has triggered its MVNO option with Verizon and is in pursuit of Incentive spectrum auction. In addition to securing its own licensed spectrum (for use in LAA), it is also possible for cable operators to lease spectrum from existing mobile operators like Sprint or from spectrum holders like Dish.

The cable operator group is expected to be the largest constituent of carrier-grade unlicensed and shared access equipment shipments, making up just under 50% of the total carrier market in 2022, followed by the mobile operator group making up 34%, and the OTT/neutral host providers with 16%. The "lull" in 2017-2018 is largely due to a steep decline in carrier Wi-Fi investment by mobile operators as they shift their focus towards LTE-based unlicensed technologies such as LTE-U/LAA. The LTE-U and Carrier Wi-Fi unit shipment to OTT/neutral host providers is expected to grow fastest at 9% CAGR (2017-2022) since it is starting from a smaller base. The mobile operator group is expected to grow at 8% CAGR, followed by the cable operators at 6% CAGR over the same period.

With the market in a formative stage in its development with many strategic dynamics (e.g., cable/mobile merger) that can dramatically change the outcome of unlicensed spectrum use, it is important to note that our current outlook is based on "business as usual" macro trends and barring any major changes to the industry structure. In the case of major mergers & acquisitions (e.g., Comcast/T-Mobile or Sprint merger), our forecast can change drastically. For example, if Comcast/Charter were to merge with T-Mobile or Sprint, our forecast of cable operator investments in Wi-Fi and MulteFire can decline significantly.

Carrier Wi-Fi Access Equipment Forecast

As more amenable LTE-centric technologies for unlicensed spectrum such as LTE-U/LAA and LWA become available, mobile operator adoption of Wi-Fi offload is expected to decline. Running LTE on unlicensed and shared bands and utilizing Carrier Aggregation to bond multiple carrier channels afford a straightforward means to increase capacity while maintaining service quality through deterministic control signaling on exclusive licensed spectrum. Meanwhile, other service providers such as cable operators and public Wi-Fi venue owners and municipalities will continue to deploy cost-effective Wi-Fi infrastructure to target a broad range of client devices. While Wi-Fi generally plays a complementary role across all service provider segments, Mobile Experts believes that mobile operators will quickly shift their "unlicensed infrastructure" investments towards LTE-based technologies such as LTE-U/LAA to opportunistically aggregate unlicensed and shared spectrum carriers alongside their licensed "anchor" carriers to increase capacity and boost user speeds. Mobile Experts forecasts that mobile operators will halt any further investments towards carrier Wi-Fi equipment after 2019, other than upgrades on select Carrier Wi-Fi infrastructure already in place as a part of LWA upgrades.



Source: Mobile Experts

Chart 8: Carrier Wi-Fi Shipment Forecast by Operator Segment, 2016-2022

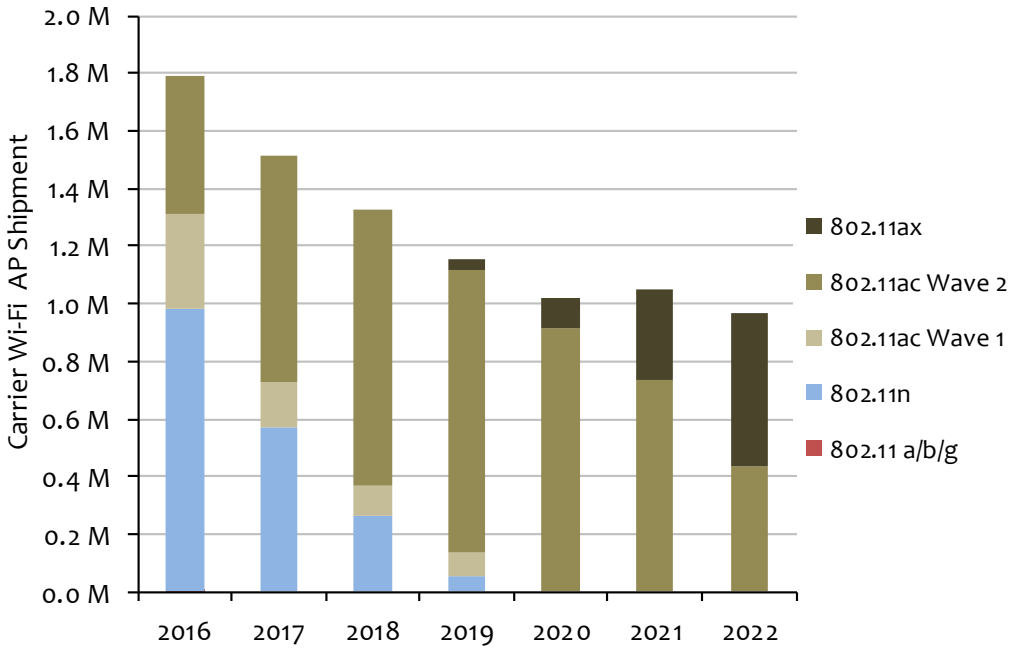
With mobile operators increasingly looking to LTE-based technologies to leverage unlicensed and shared spectrum bands, Mobile Experts expects the overall Carrier Wi-Fi segment to experience a secular decline. While the Carrier Wi-Fi market is expected to find a stable foothold in broadband CPE and outdoor deployment use cases primarily by non-mobile operators, it may experience a further decline if: 1) LTE-unlicensed ecosystem build enough scale over time; and, 2) cable operators increase wireless infrastructure investment towards LTE in pursuit of wireless network buildout for their mobile services.

In aggregate, Mobile Experts forecasts the Carrier Wi-Fi segment of the "unlicensed carrier infrastructure" market to decline -9% CAGR (2017 to 2022), even though unit shipments to the OTT/neutral host provider segment is expected to grow modestly at 3% during that period. Again, this pull-back is mainly attributed to the mobile operators' shift towards LTE-based unlicensed technologies such as LTE-U/LAA, LWA, and CBRS. In addition, Mobile Experts believes that as cable operators' interest and aspiration in mobile industry grows, their preference for LTE-based technologies will also grow thus limiting their further interest in Carrier Wi-Fi especially for outdoor and venue deployments.

Carrier Wi-Fi 802.11 Technology Adoption Trend

The Carrier Wi-Fi segment generally tends to trail the Retail/SOHO and Enterprise markets when adopting latest 802.11 technology. The overall Wi-Fi market generally sees the Retail segment adopting latest Wi-Fi technologies (e.g., 802.11n, 802.11ac, 802.11ax, and so on), followed by enterprises, and then service providers. While the peak of 802.11ac adoption is

in full force in the Retail and Enterprise segments, the Carrier Wi-Fi market is forecasted to adopt 802.11ac in 2017-2018 timeframe with an initial ramp of 802.11ax access equipment coming to market in 2019. The 802.11ac share of the Carrier Wi-Fi market is expected to reach over 60% in 2017 and reach peak of about 90% in 2020, and cede its majority share to 802.11ax in 2022.



Source: Mobile Experts

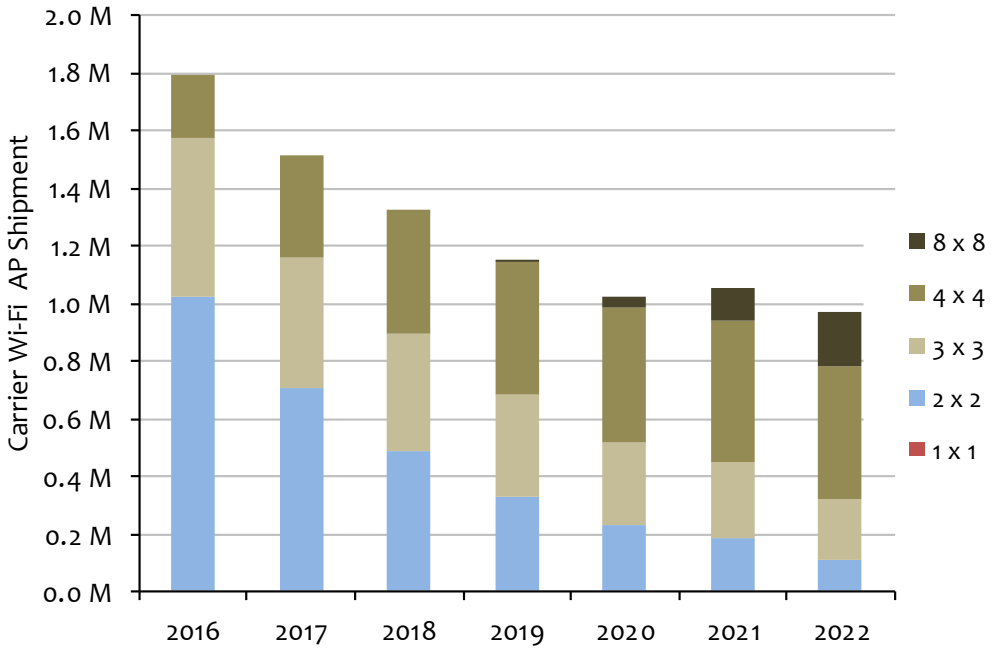
Chart 9: Carrier Wi-Fi 802.11 Technology Adoption Trend, 2016-2022

While mobile operators shift their capital expenditure dollars towards the LTE-unlicensed technologies (i.e., LTE-U/LAA and LWA), Mobile Experts foresee cable operators and OTT/neutral host operators like Boingo to continue rely on the traditional Wi-Fi technology path. Starting 2020, we expect to see a greater adoption of Carrier Wi-Fi units as the operators deploy or upgrade 802.11ax units.

Carrier Wi-Fi MIMO Trend

A majority of Carrier Wi-Fi access equipment supports MIMO since it was introduced with 802.11n. Using MIMO results in greater data rates, improved range, and overall improvement in Wi-Fi network performance. The introduction of multi-user MIMO (MU-MIMO) in 802.11ac wave 2 is expected to be well received especially in Carrier market segment where network congestion is increasingly becoming a serious problem operating in unlicensed spectrum bands. MU-MIMO alleviates network congestion by allowing multiple client devices to access the radio channel (assuming those client devices also support MU-MIMO). With MU-MIMO, even 1x1 legacy Wi-Fi clients can be serviced through an access

point. With increasing adoption of 802.11ac and eventually 802.11ax, 4x4 MIMO configuration is expected to dominate share of Carrier Wi-Fi access equipment. While some high-end 802.11ac products (enabled through Quantenna's proprietary "wave 3" 10G chipset for example) support 8x8 MIMO, a bulk of Carrier Wi-Fi products is forecasted to support 8x8 MIMO configuration as 802.11ax rolls out en masse.



Source: Mobile Experts

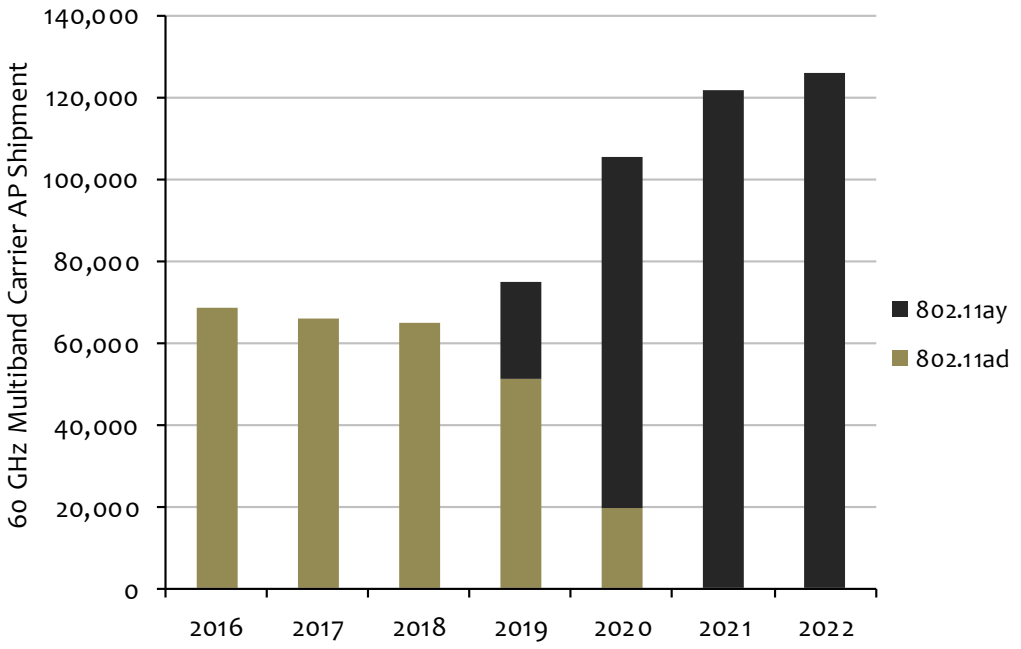
Chart 10: Carrier Wi-Fi MIMO Configuration Trend, 2016-2022

Carrier Wi-Fi 60 GHz (802.11ad and 802.11ay) Outlook

60 GHz unlicensed spectrum access through 802.11ad (WiGig) and eventually 802.11ay promises new Carrier Wi-Fi market opportunities for point-to-point or point-to-multipoint outdoor backhaul. While there are myriad enterprise applications for the 60 GHz access, including wireless connectivity to VR headsets and other enterprise appliances, HDMI/USB replacement, campus backhaul to name a few, Mobile Experts believes that carrier market opportunity in outdoor deployments will be limited in the near term.

While OTT wireless service providers who lack owned network infrastructure may look to the huge bandwidth available in the 60 GHz millimeter wave band for multi-Gbps backhaul, we believe traditional cable and mobile carriers will primarily look to their owned wireline infrastructure for backhaul. For dense urban wireless deployments for over-the-top service providers with limited owned infrastructure, Mobile Experts believes that 60 GHz access can be a good alternative solution for short-range (less than 1000 feet) high-capacity backhaul, or even fixed wireless access. With the IEEE task group expected to complete the 802.11ay

specification draft later this year, Mobile Experts expects the 802.11ay equipment to come to market in the 2019 timeline. With higher capacity and greater range (about 1000 feet) with channel bonding and MIMO features, Mobile Experts believes the market opportunity will certainly grow for the 802.11ay adoption. However, the market opportunity in the carrier segment is tempered by increased fiber investments in preparation for 5G, which is a headwind for wireless backhaul sector in general. Though we do not track the enterprise segment in detail, Mobile Experts believes that the 802.11ad / ay market opportunities in the Enterprise and Retail/SOHO markets are generally much brighter than the Carrier market.



Note: Most 60 GHz carrier deployments used for backhaul, not access.

Source: Mobile Experts

Chart 11: Carrier Wi-Fi 60 GHz Adoption Trend, 2016-2022

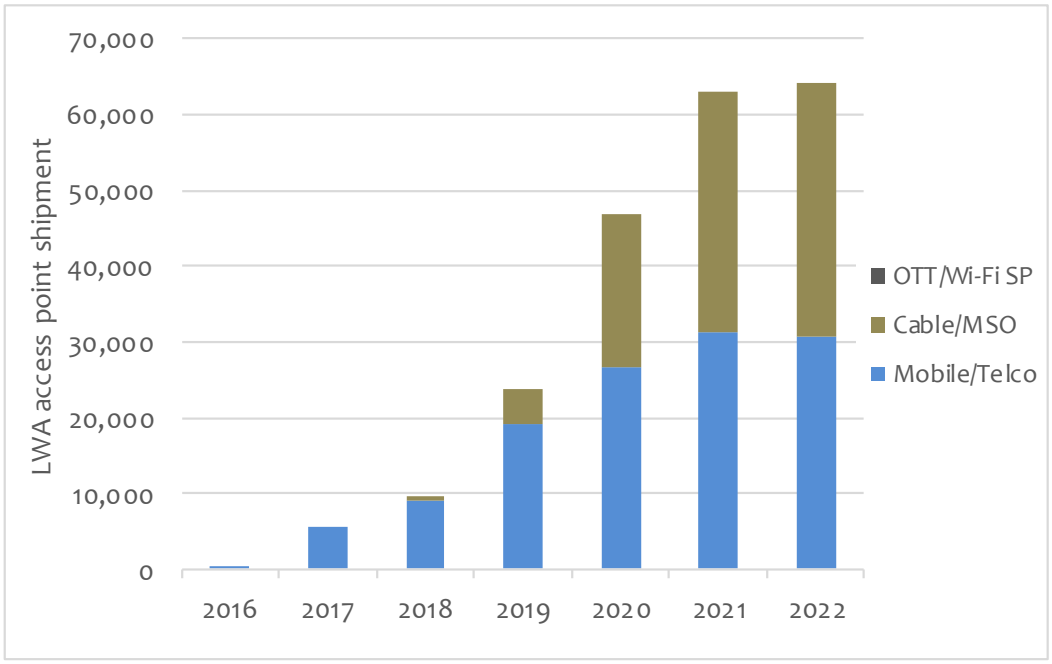
LTE-Wi-Fi Aggregation (LWA) Access Equipment Forecast

For mobile operators that have a meaningful installed base of Wi-Fi access points, we expect them to work with eNodeB and Wi-Fi infrastructure vendors to upgrade their LTE RAN and carrier Wi-Fi equipment to support LWA and LWIP. By this way, they can fully leverage the installed base of Wi-Fi infrastructure for boosting capacity and load balancing traffic demands.

While LWA can theoretically offer downlink aggregation (and uplink aggregation through eLWA in 3GPP Release 14) by leveraging existing Wi-Fi infrastructure, the market adoption has been very limited to date. Besides some trials, actual market deployments have been

very limited to date. Besides a couple of minor planned deployments in Asia – Chunghwa Telecom in Taiwan and M1 in Singapore, LWA has not really taken off. A similar LTE Wi-Fi aggregation method called LWIP, which aggregates LTE and Wi-Fi links at IP layer has not gained any traction since last year's report. One of the reasons for the lack of momentum behind LWA may perhaps be added integration and interoperability testing of Wi-Fi and LTE base stations required to ensure end-to-end service assurance. Besides the infrastructure testing, the LWA requires dual-connectivity feature on client devices. Based on quick market survey, device support for this feature appears very limited. Besides some tier 2 devices like HTC and regional smartphones, this feature is not yet supported on latest smartphones from Samsung and Apple. This may be a sign that an operator demand for LWA and LWIP is scant.

While some cable operators with significant Wi-Fi infrastructure assets may want to explore LWA to boost user throughput experience on their MVNO mobile service offerings, without major mobile operator push for this feature, it will be difficult for cable operators to incentivize device vendors to support this feature when their purchase order volumes are significantly less than those of mobile operators. For this reason, Mobile Experts expects this experiment to be limited in scope and scale as there is a big uncertainty around how influential they will be in convincing key device vendors to support the necessary dual-connectivity feature.



Source: Mobile Experts

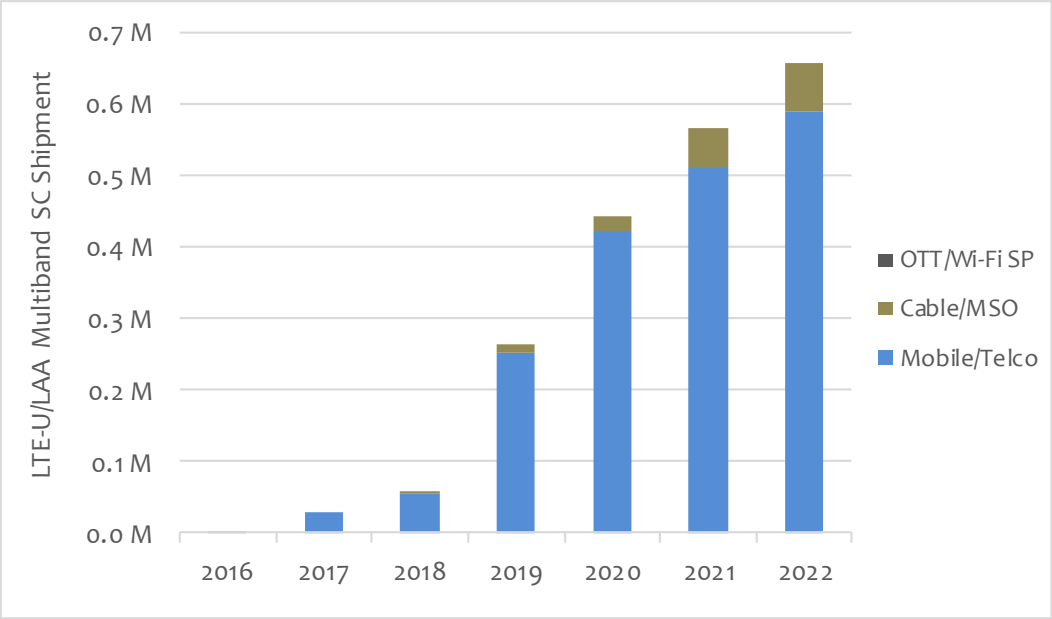
Chart 12: LWA Shipment Forecast by Operator Segment, 2016-2022

Mobile Experts currently forecasts a very modest adoption of LWA among carrier groups. One key factor that can dramatically change this outlook is China Mobile. China Mobile has a significant Wi-Fi infrastructure deployment -- about 6 million units by our estimate. China Mobile has carried out some limited LWA trials, and if it decides to massively roll out LWA,

our forecast will surely change. Based on alternative unlicensed LTE technology options at hand, Mobile Experts now believes that China Mobile is likely to choose LAA over LWA, or may simply look to other licensed spectrum bands such as 3.5 GHz 5G deployment. There is a large degree of uncertainty in our forecast at the moment with regard to plans for China Mobile's Wi-Fi upgrades

LTE-U/LAA Access Equipment Forecast

Mobile Experts forecasts LTE-U and its standards-based version, LAA, to be a dominant means by which mobile operators will leverage unlicensed and shared spectrum bands below 6 GHz. The licensed-assisted manner allows the mobile operators to more effectively leverage the unlicensed spectrum bands by managing service quality through control signaling on licensed anchor band which is, by definition, exclusive to a mobile operator. Mobile Experts believes that mobile operators will opportunistically leverage unlicensed 5 GHz band in the near term, and the CBRS shared spectrum in the 3.5 GHz band in 2018 and 2019 to increase capacity as well as tout "Gigabit LTE" capabilities as they expand small cell rollouts with LTE-U/LAA and CBRS multiband capabilities and seed the market with Category 16 (1Gbps downlink) smartphones. This trend has already started and is expanding quickly as operators complete trials and announce 4.5G LTE-Advanced Pro network rollouts along with introduction of Category 16 devices such as Samsung Galaxy 8. According to Global Mobile Supplier Association (GSA), there are already 19 LTE-Advanced Pro networks live and more are coming.



Source: Mobile Experts

Chart 13: LTE-U/LAA Shipment Forecast by Operator Segment, 2016-2022

In general, Mobile Experts expects mobile operators with limited spectrum holdings to leverage LAA to expand capacity and user throughput speeds. For example, T-Mobile and

Verizon have been very public about their intentions to deploy LTE-U and LAA networks. T-Mobile has recently launched LTE-U networks in several markets, and we expect the LTE-U rollout to expand to other markets rest of this year and the next. Likewise, Verizon is expected to also launch LTE-U networks later this year and upgrade those LTE-U small cells to LAA in early 2018. Mobile Experts believes that the 5 GHz band may not be heavily loaded in urban environments for outdoor applications as most of Wi-Fi deployments are for indoor applications with low-power radios. For this reason, we expect mobile operators to take advantage of this situation by deploying LTE-U/LAA small cells initially for outdoor applications at key strategic locations such as public venues like stadiums and transportation hubs so that they can claim "Gigabit LTE" services as they rollout Category 16 user devices.

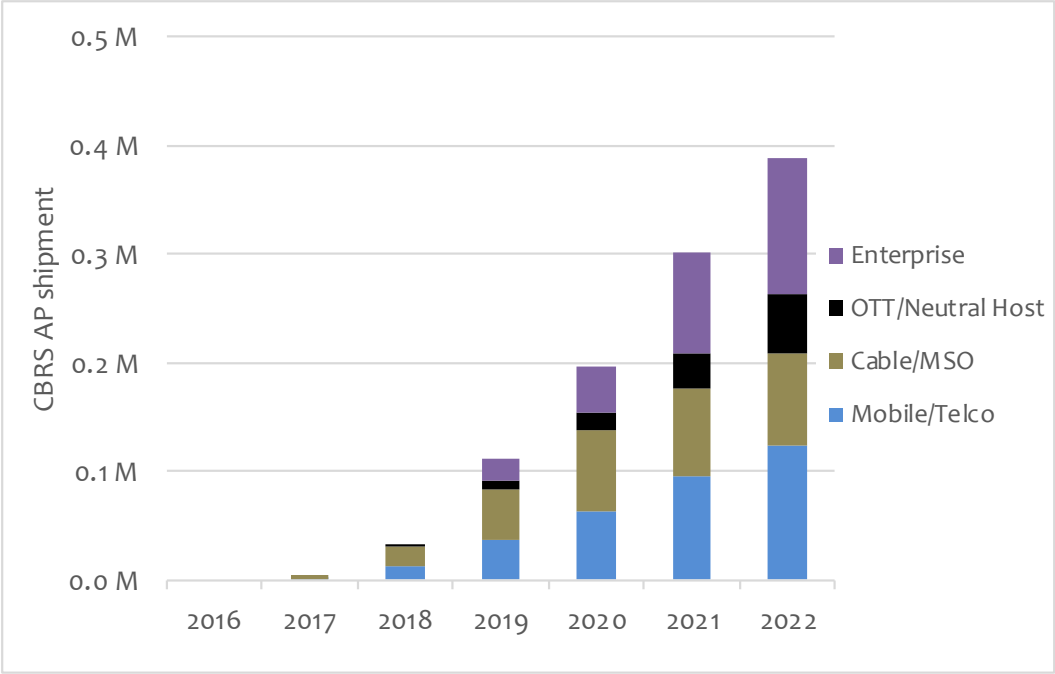
While the scale of market rollout will likely be limited, there is a possibility that cable operators may also deploy LAA with potential licensed spectrum acquisition (e.g., Comcast's 600 MHz spectrum purchase) or lease (e.g., spectrum lease from DISH) to augment owned mobile network capacity. There is a lot of uncertainty around this prospect, but we have denoted this possibility in our forecast.

CBRS Access Equipment Forecast

The CBRS band represents a new "mid-band" spectrum available for use by multiple stakeholders in the United States. An innovative three-tier licensing structure incentivizes incumbent and new entrants to use the 150 MHz of fresh spectrum for various wireless services. Our view of the U.S. mobile operators' position on the CBRS band has changed somewhat. Mobile Experts believes that the mobile operators will be more inclined to leverage the band as soon as the sharing infrastructure including SAS and ESC are certified (expected end of 2017). This view is driven by the following observations and market dynamics:

1. 3.5 GHz is becoming a preferred sub-6 GHz band for 5G as regulators and operators especially in China and APAC target this band;
2. Hence, the semiconductor ecosystem around this band is expected to gain scale and lower cost; thus, further gain momentum as a cost-effective band to "anchor" 5G network and services;
3. CTIA, as a US lobbying arm of the mobile industry, has been active in FCC petitioning[13] and potentially as a SAS operator – we take these signs as mobile operators' keen interest to favor the use of the CBRS band for their benefit; and,
4. Spectrum, whether licensed, unlicensed, or shared, is a raw commodity that drives the wireless industry; mobile operators will leverage the "mid-band" CBRS spectrum whether their petitions for rule changes to lengthen the PAL licensing term and increase licensing footprint to Partial Economic Area basis from census tract.

[13] CTIA FCC petition to lengthen the PAL license term to 10 years and enlarging license parcel size, June 16, 2017



Source: Mobile Experts

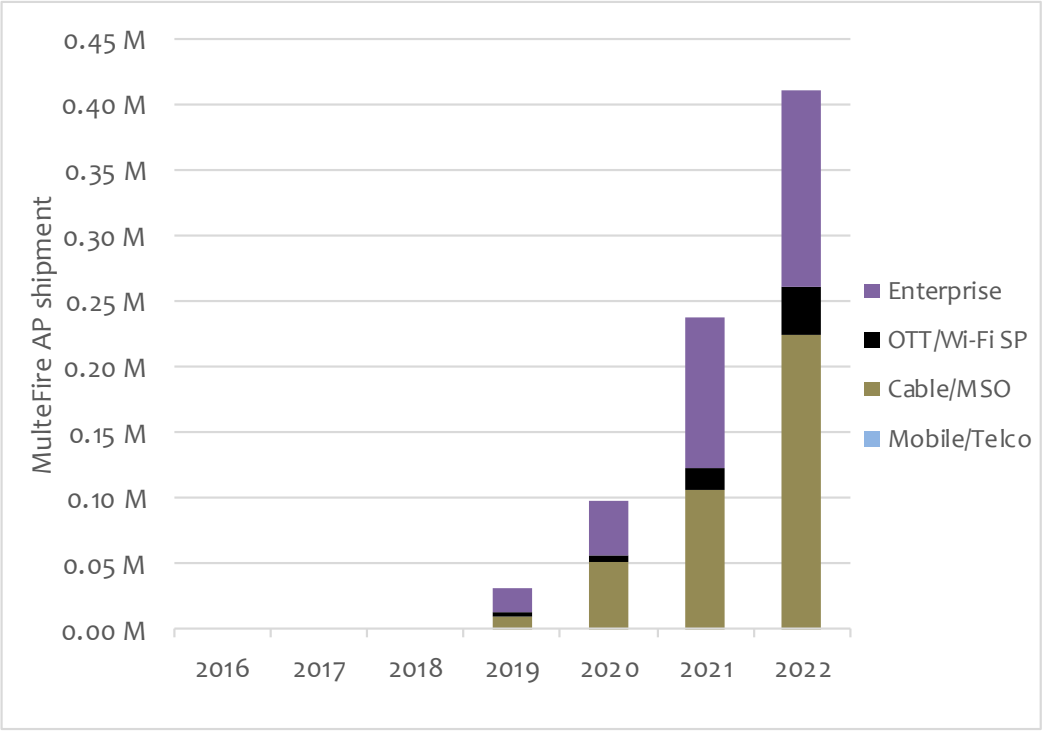
Chart 14: CBRS Shipment Forecast by Operator Segment, 2016-2022

Mobile Experts expects the mobile operators to deploy CBRS multiband small cells to leverage the shared spectrum band in LAA fashion - i.e., aggregate carriers across both shared and licensed spectrum bands to increase capacity and enhance user throughput. In the near term (2017-2018), Mobile Experts forecasts the cable operators to be more aggressive in outdoor and indoor deployments. By the end of the forecast period, Mobile Experts forecasts the mobile operators to deploy about 32% of all CBRS radios as multiband small cells in 2022. Cable operators are expected to deploy about 22% of all CBRS radios as standalone small cells in 2022. Moreover, large "tech-savvy" enterprises and some neutral host providers are also likely to deploy over 30% of all CBRS radios in 2022 to take advantage of new CBRS spectrum band for enterprise applications that require greater service quality.

The overall CBRS access equipment market is forecasted to be poised for a tremendous growth – 140% CAGR (2017-2022). Starting from a small base, the three-digit percentage growth is plausible, with a key assumption that multiple service provider groups and some large enterprises expected to participate based on the innovative licensing rules. If the CBRS licensing rules were to be changed in favor of incumbent mobile operators with higher spectrum costs and other onerous use terms, expected participation from other groups especially OTT/neutral host service providers and large enterprises may wane and likely reduce our projections.

MulteFire Access Equipment Forecast

MulteFire attempts to broaden the appeal of LTE use in the unlicensed bands by allowing "standalone" LTE to run on unlicensed bands without a licensed anchor. In effect, MulteFire allows a service provider without licensed spectrum holdings to run LTE. There is a perceived value of being able to run LTE to take advantage of higher service quality afforded with coordinated and deterministic scheduling in LTE vs. "collision avoidance" scheduling in Wi-Fi. While it is still too early to assess the merits of 802.11ax vs. MulteFire in the 5GHz unlicensed band and 3.5 GHz shared band, Mobile Experts expects some cable operators, OTT/neutral host providers, and a few large enterprises to adopt MulteFire to assess its merit especially in the CBRS band. Business cases for MulteFire still need to be proven out, such as neutral host in-building wireless. MulteFire is expected to be trialed by non-mobile operators like the cable operators, OTT/neutral host providers, and enterprises. With the MulteFire spec 1.0 for mobile broadband recently released, Mobile Experts predicts the carrier demand for MulteFire will largely be confined to non-mobile operators and scale of rollout will likely be limited. For the MulteFire segment to scale, the economics of MulteFire and specific use cases targeted must be meaningfully differentiated against other technology and ecosystem alternatives. Thus far, such differentiations are few, and Mobile Experts forecasts a modest uptake.



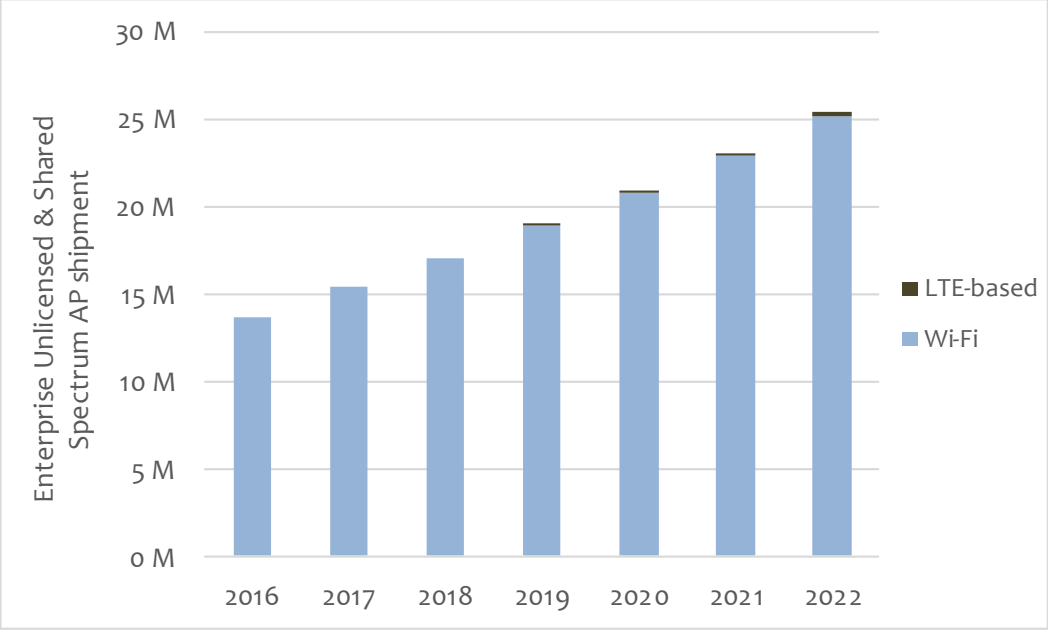
Source: Mobile Experts

Chart 15: MulteFire Shipment Forecast by Operator Segment, 2016-2022

LTE-U and Wi-Fi Penetration of Carrier and Enterprise Segments

One of the interesting dynamics of LTE and Wi-Fi technologies increasingly operating in unlicensed spectrum bands is the adoption trend of these technology families in the carrier and enterprise segments. Will the LTE-Unlicensed technologies and ecosystems of LTE-U, LAA, LWA, CBRS, and MulteFire swiftly take share away from Wi-Fi infrastructure market in the enterprise space? How will the LTE-Unlicensed technologies impact the Carrier Wi-Fi equipment market? Before the advent of the LTE-Unlicensed technologies and ecosystems, both the carriers and enterprises relied solely on Wi-Fi to take advantage of unlicensed spectrum. With LTE-Unlicensed technology alternatives coming to market, there appears to be a direct competition between Wi-Fi and LTE at a surface level.

In a closer inspection, Mobile Experts believes that the "us vs. them" dynamic between Wi-Fi and LTE communities has been overblown. The two technologies fundamentally serve different end markets that is historically rooted in their origins. While we expect certain niche segments of the enterprise market to adopt "standalone" LTE-Unlicensed technology such as MulteFire in the unlicensed and shared spectrum bands, a predominant base of the enterprise market will continue to adopt the traditional Wi-Fi technology roadmap, upgrading from 802.11n and 802.11ac base to 802.11ax in near future. Moreover, traditional enterprise Wi-Fi market will likely adopt 60 GHz spectrum use through 802.11ad and 802.11ay in some cases such as wire replacement and "tri-band" (2.4 GHz, 5 GHz, and 60 GHz) router deployment use cases. Considering the huge Enterprise Wi-Fi infrastructure market, the LTE penetration of the traditional Enterprise Wi-Fi market, namely through MulteFire on the 5 GHz and 3.5 GHz CBRS bands, is expected to be very minimal -- just over 1% in 2022.



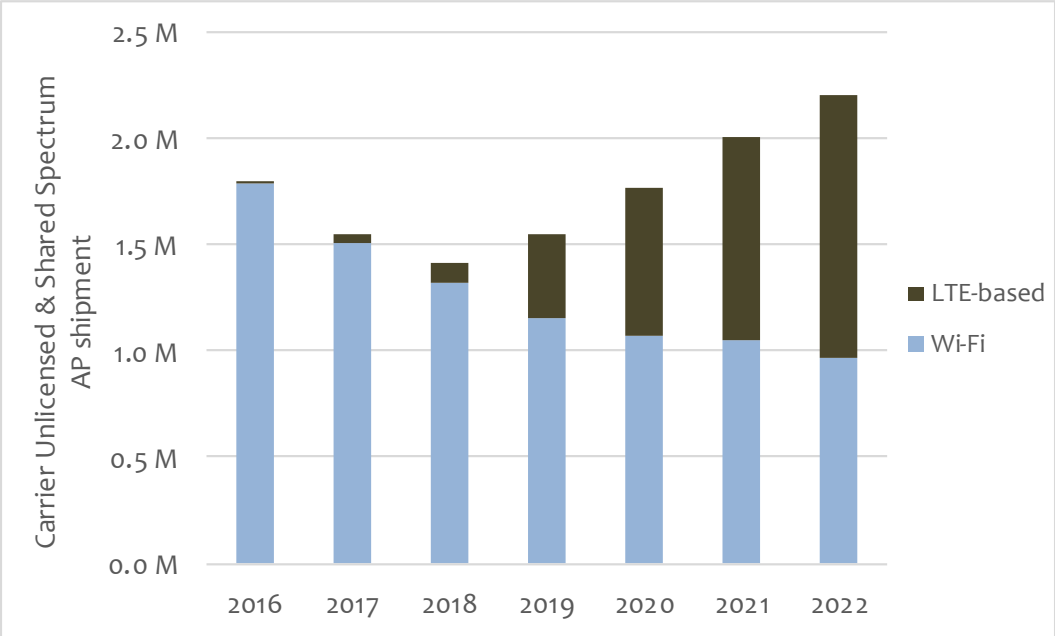
Source: Mobile Experts

Chart 16: Enterprise Adoption of LTE-U and Wi-Fi Access Equipment, 2016-2022

This conservative outlook is based on following drivers and key assumptions:

1. Most enterprises will adopt backwards-compatible Wi-Fi roadmaps to service the broadest and most diverse set of client devices used in enterprise environment;
2. MulteFire ecosystems for enterprise use cases are not expected to mature until 2019 – the ramp will take some time;
3. A critical mass of CBRS-ready client device ecosystem will take some time to develop – enterprises will be reluctant to invest in CBRS infrastructure until the device ecosystem is broad enough, even if presumed service quality advantages of LTE are compelling to adopt; and,
4. Mobile operators can heavily influence smartphone feature support for MulteFire or CBRS, thus ultimately influence whether LTE-unlicensed use in enterprise context is meaningful.

Meanwhile, the carrier adoption of LTE-based technologies for the unlicensed and shared spectrum bands is expected to shift significantly away from traditional carrier Wi-Fi infrastructure to LTE-U/LAA, LWA, and CBRS as the ecosystems mature in the coming years. The unlicensed and shared spectrum small cell technologies offer better economics and better control over service quality in license-assisted manner. For these reasons, mobile operators are motivated to ramp up LTE-U/LAA small cells and tout higher speed service offerings as a result. Aggregating carriers across licensed, unlicensed and shared spectrum bands offer economical means to increase network capacity and enhance user throughput speeds, while managing service quality through deterministic control signaling on licensed carrier. A majority of "LTE" access equipment forecast as shown below is expected to be deployed as LTE-U/LAA multiband small cells by mobile operators. Meanwhile, traditional carrier Wi-Fi access points are expected to be deployed by fixed/cable operators as well as OTT Wi-Fi operators such as venue owners and municipalities. With expected maturity of LTE-U/LAA, LWA, and MulteFire ecosystems, LTE penetration of the traditional carrier Wi-Fi market is expected to reach over 56% in 2022.



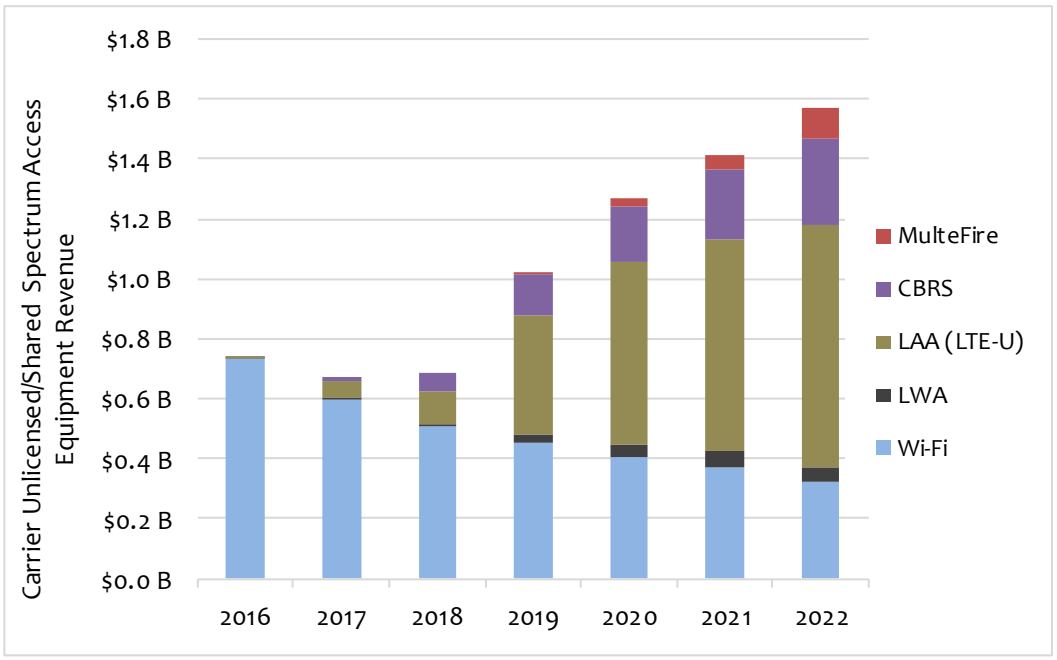
Source: Mobile Experts

Chart 17: Carrier Adoption of LTE-U and Wi-Fi Access Equipment, 2016-2022

LTE-U and Carrier Wi-Fi Revenue Forecast[14]

The carrier wireless infrastructure market leveraging unlicensed and shared spectrum (i.e., "LTE-U and Carrier Wi-Fi" access equipment market) is expected to grow robustly as mobile operators worldwide ramp up LTE-Advanced Pro network deployments. For operators with limited licensed spectrum holdings and those in highly competitive markets are expected to leverage LTE-U/LAA. Also, both cable and mobile operators in the United States are expected to take advantage of CBRS shared spectrum bands to further augment their network capacities. The cumulative LTE-U and Carrier Wi-Fi equipment market is expected to grow from about $670M today to $1.6B in 2022 – 19% CAGR growth. Excluding Carrier Wi-Fi access equipment sales, the "LTE-only" segment of the carrier unlicensed access equipment market is expected to grow at about 80% CAGR (2017-2022), reaching almost $1.25B in 2022!

[14] Please note that the "LTE-U" market overlaps with Mobile Experts' *Small Cell* forecasts. The LTE-U market figures are subsets of *Carrier Outdoor* and *Carrier Indoor* forecasts in the *Small Cell 2017* report.

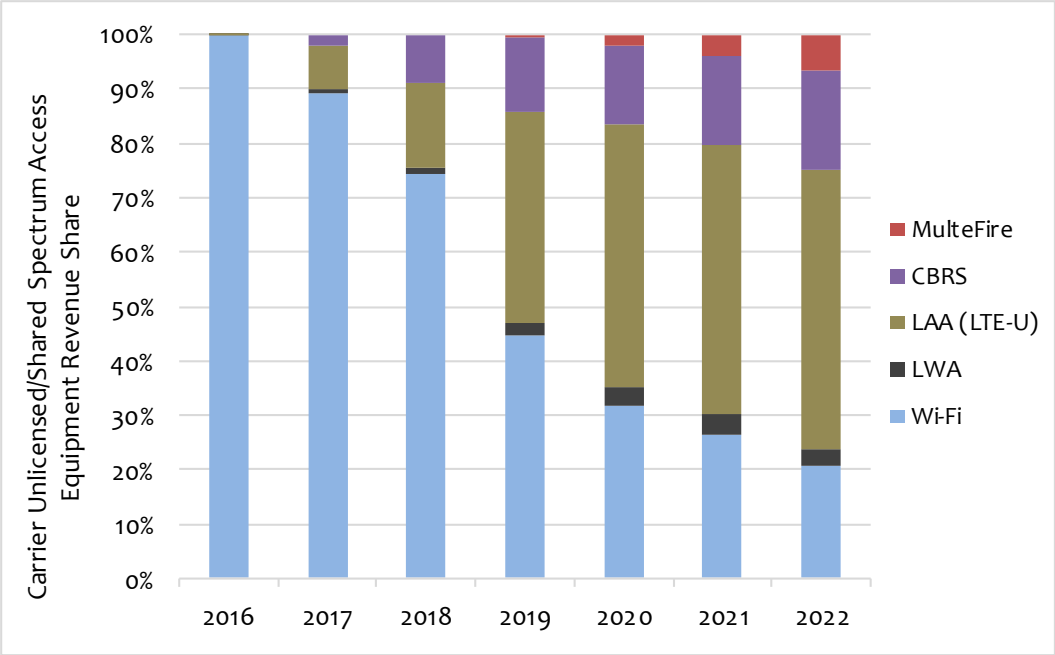


Source: Mobile Experts

Chart 18: Carrier Access Equipment Revenue Forecast by Unlicensed and Shared Spectrum Technology, 2016-2022

Meanwhile, the Carrier Wi-Fi segment of the carrier unlicensed access equipment market is expected to continue its downward trend. It is expected to decline at (12%) CAGR from about $600M in 2017 to about $325M in 2022. Most of that business will be derived from fixed/cable operators and other OTT/Wi-Fi centric service providers such as wireless ISPs in underserved markets.

A cumulative share of "LTE-unlicensed" segment that support LTE-U/LAA, MulteFire, CBRS, or LWA is forecasted to grow from 10% of the total carrier unlicensed access equipment market in 2017 to about 80% in 2022.



Source: Mobile Experts

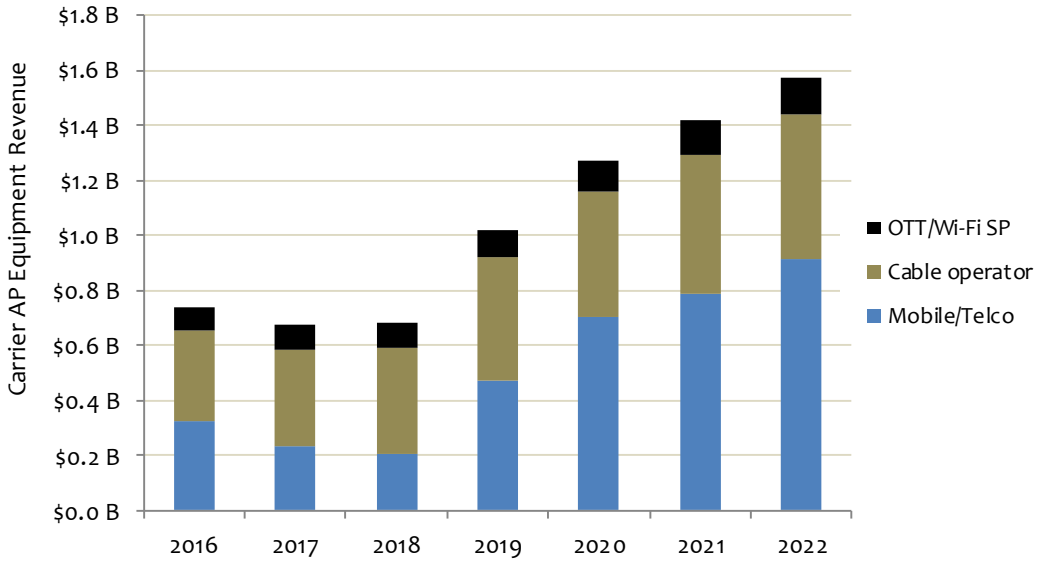
Chart 19: Carrier Access Equipment Revenue Share Forecast by Unlicensed and Shared Spectrum Technology, 2016-2022

In terms of carrier segments, U.S. cable operators are expected to be very active in looking to harness the 3.5 GHz CBRS band. In addition to continued investments in outdoor and indoor Wi-Fi infrastructure, to aid in fixed broadband and newly launched MVNO businesses, the newly available 150 MHz of CBRS spectrum and its fast-growing ecosystem offer an excellent opportunity for the cable operators to stand up LTE-based wireless network.

Mobile operators, meanwhile, will be keen to opportunistically aggregate carriers across licensed, unlicensed and shared spectrum bands to increase network capacity and offer higher-speed user throughput to subscribers with latest UE Category 16 smartphones (e.g., Samsung Galaxy 8 can provide a 1-Gbps downlink with a software update). For operators with limited spectrum holdings, LTE-U/LAA small cells in concert with latest smartphones offer a good pathway towards "Gigabit LTE" and 5G services. Some of the mobile operators' increasing capital expenditures towards small cells will certainly encompass LTE-U/LAA multiband units, as will the CBRS radios for both outdoor and indoor units.

Not surprisingly, the mobile operators are expected to be the biggest purchasers of unlicensed carrier access equipment, most notably LTE-U/LAA small cells. Mobile Experts forecasts that cable operators--especially those in the United States--will be just as active in unlicensed carrier access. We expect the cable operators to be aggressive in deploying CBRS outdoor small cells to augment their wireless network capacity, and increasingly look towards LTE-based unlicensed use even though they will continue to invest in Carrier Wi-Fi gears. Mobile operators make up the largest portion of the carrier infrastructure

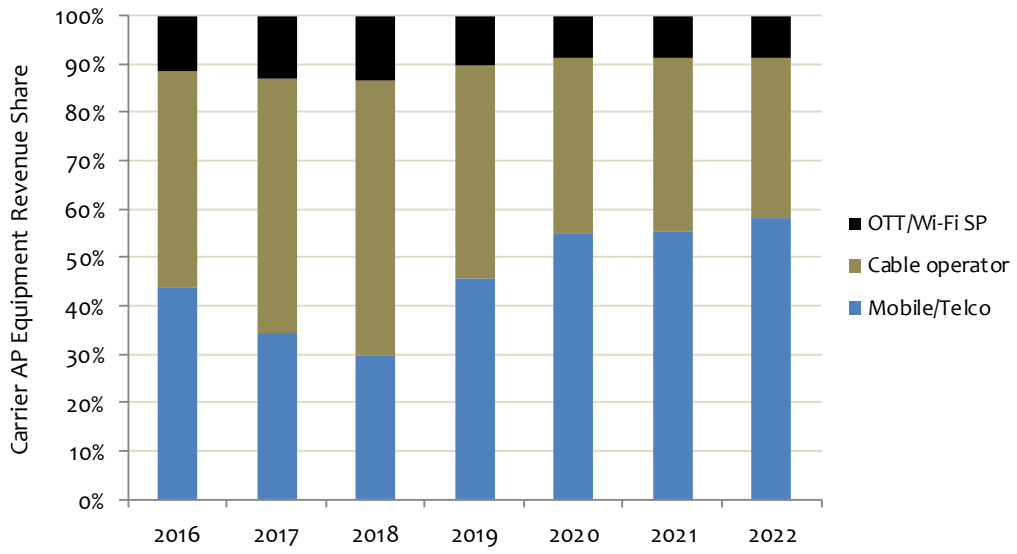
investment for unlicensed/shared use (58%), followed by the cable operators (33%), then the OTT/Wi-Fi operators (9%) at the end of our forecast period.



Source: Mobile Experts

Chart 20: Carrier Access Equipment Revenue Forecast by Operator Segment, 2016-2022

While mobile operators conduct LAA trials and initial deployments during 2017-2018, their share of unlicensed spectrum use is expected to decline as a percentage of the overall carrier unlicensed wireless infrastructure market. With expected uptake of LAA for carrier aggregation across unlicensed and shared spectrum bands, the mobile operators' share of the overall market is expected to rise to 60% in 2022.

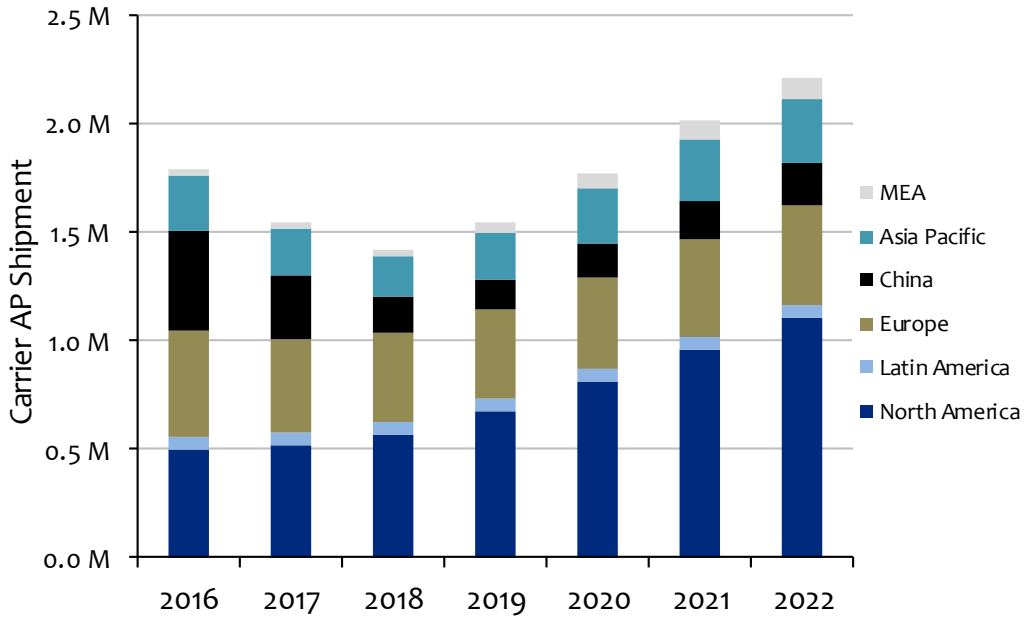


Source: Mobile Experts

Chart 21: Carrier Access Equipment Revenue Share by Operator Segment, 2016-2022

6 REGIONAL OUTLOOK

The carrier-grade access equipment (including LTE-unlicensed small cells and carrier Wi-Fi access points) shipment is forecasted to grow at over 20% CAGR (2017-2022) to reach over 2.5M units in 2022. While the overall market is expected to experience a lull in 2018 as Carrier Wi-Fi market declines while the LTE-unlicensed ecosystem ramps up, once the LTE-U/LAA, LWA, and CBRS ecosystems ramp up, the market is expected to pick up momentum. Regionally, North America is expected to see a strong growth as competitive market dynamics force the mobile operators to leverage unlicensed as well as shared CBRS bands to augment their network capacity. In addition, the CBRS ecosystem is expected to bring additional players including cable operators and OTT/neutral host providers to make infrastructure investment in this band. Other regions where licensed spectrum is limited such as parts of Asia-Pacific and MEA are also expected to leverage LTE-U/LAA to bolster network capacity.



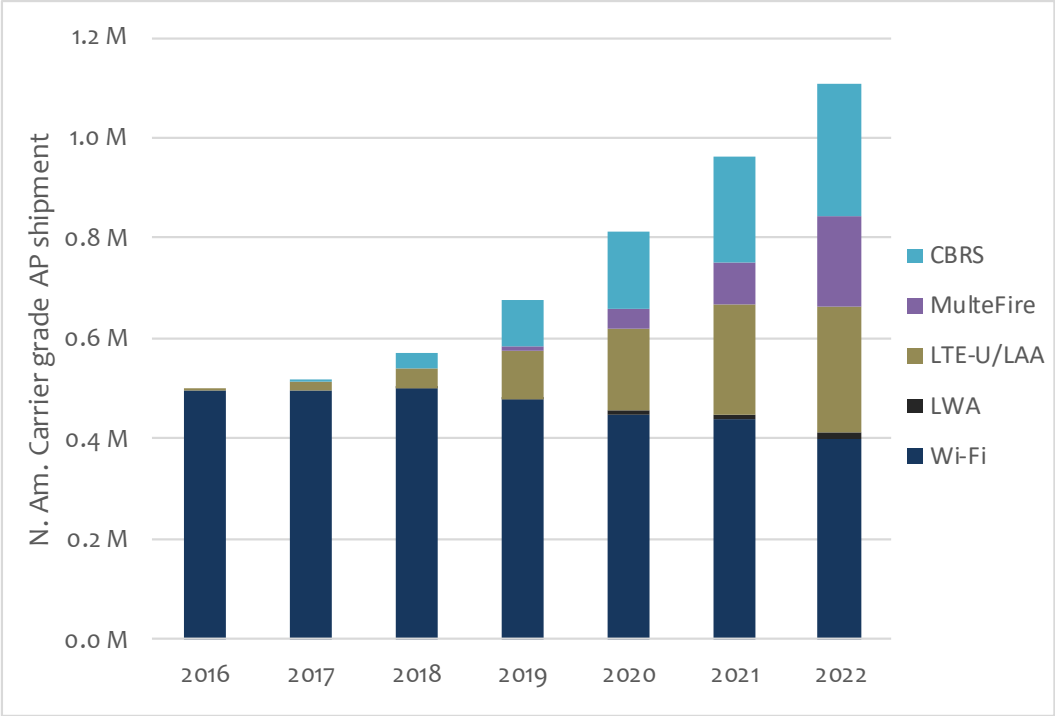
Source: Mobile Experts

Chart 22: Carrier Unlicensed Access Equipment by Region, 2016-2022

North America

The North American region represents the biggest market for "carrier unlicensed/shared spectrum access infrastructure" (LTE-U and Carrier Wi-Fi) market with almost 1.1M unlicensed/shared spectrum access equipment or small cells in 2022. While Mobile Experts forecasts a mid-single-digit decline in traditional carrier Wi-Fi from 2017 to 2022 as mobile operators, and cable operators to a lesser degree, shift investment towards LTE-based technologies, primarily LTE-U/LAA and CBRS, the overall market including Carrier Wi-Fi is

expected to grow at over 16% during that period. The combined CBRS and LTE-U/LAA access equipment is forecasted to represent the largest share of the overall unlicensed/shared carrier access equipment market with about 23% each in 2022. A significant share of CBRS is largely based on the assumption that the current CBRS rules will be maintained and that cable operators, OTT/neutral host providers, and some large enterprises, will make capital expenditure investment in CBRS radios alongside mobile operators. If this dynamic were to change over the next year, and CBRS rules heavily favor incumbent mobile operators, our forecast of CBRS growth will likely be reduced. It should be noted that Mobile Experts believes that a bulk of CBRS units deployed by mobile operators will be employed in license-assisted manner, while cable operators will deploy in a standalone LTE-TDD (MulteFire) mode.

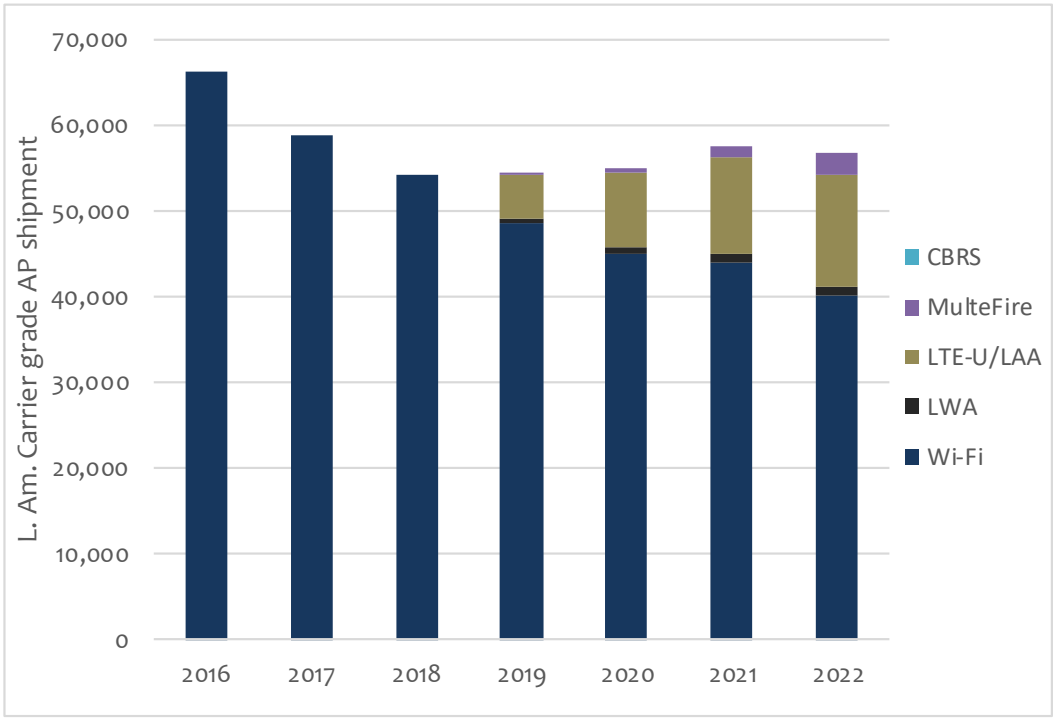


Source: Mobile Experts

Chart 23: Carrier Unlicensed Access Equipment, North America, 2016-2022

Latin America

The scale of carrier AP shipments in Latin America pales in comparison to the North American market. However, the mobile operators in the region are expected to adopt LAA and LWA to a lesser extent as the learnings from market trials in the leading markets like North America become well understood and infrastructure and client device ecosystems mature and gain scale. The scale of these LTE-unlicensed deployments is likely very small during the initial launch in 2019 and beyond. While the overall market is expected to be "flat-ish" as the traditional carrier Wi-Fi segment is expected to see a moderate decline of -7% CAGR (2017-2022) while LTE-unlicensed technology adoption slowly ramps up.

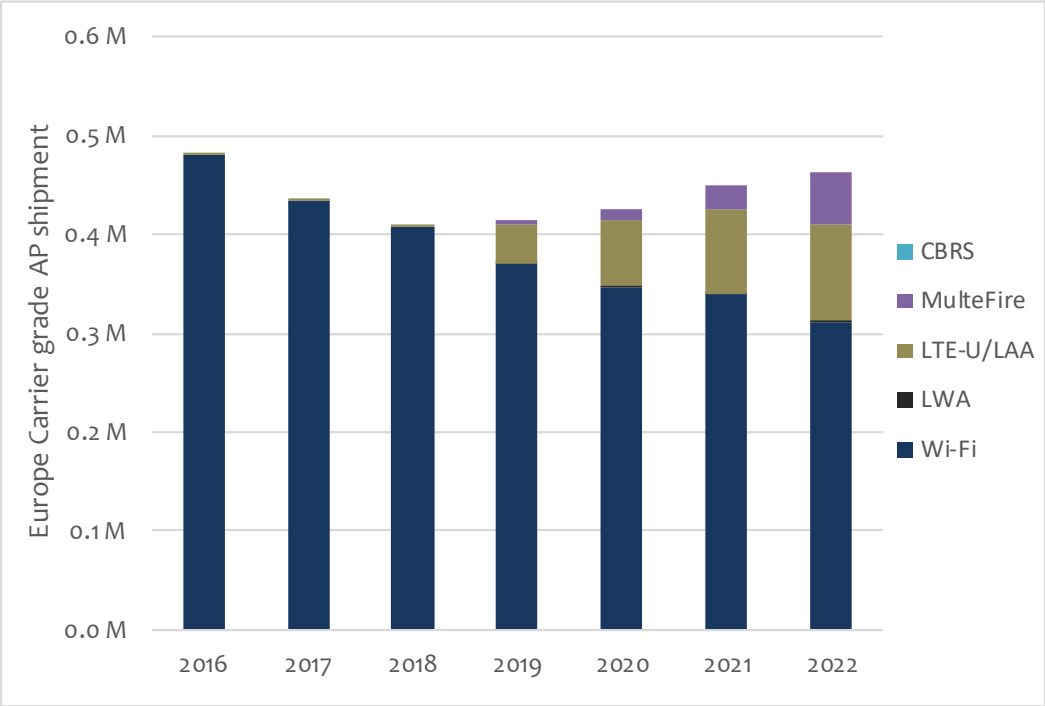


Source: Mobile Experts

Chart 24: Carrier Unlicensed Access Equipment, Latin America, 2016-2022

Europe

With a diverse mix of fixed and mobile operators, Europe represents a sizable market for carrier access infrastructure market in general. Last year, Mobile Experts forecasted a higher growth prospects for LAA and LWA in the region fueled by "quad play" competitive dynamics. While some major operators have conducted LAA trials in 2015 and 2016, announcement of actual deployments has been muted. Based on lack of commercial deployments beyond the initial trials and demos, we have tampered a growth outlook for LAA and LWA in the region. With mobile and fixed operators largely settling into a more stable competitive environment after a flurry of mergers and acquisitions (e.g., BT/EE merger, Liberty Global/Vodafone joint venture in the Netherlands, etc.) in the past couple of years, Mobile Experts expects major operators to opportunistically deploy LAA small cells on path towards LTE-Advanced Pro network rollouts before 5G NR commercial rollouts after 2020 timeline. Mobile Experts forecasts a minimal MulteFire adoption as shared spectrum use is still in formative stages of development in Europe. Although there is Licensed Shared Access (LSA) plan being discussed in some parts of Europe, the potential scale is expected to be minimal in the near to mid-term.

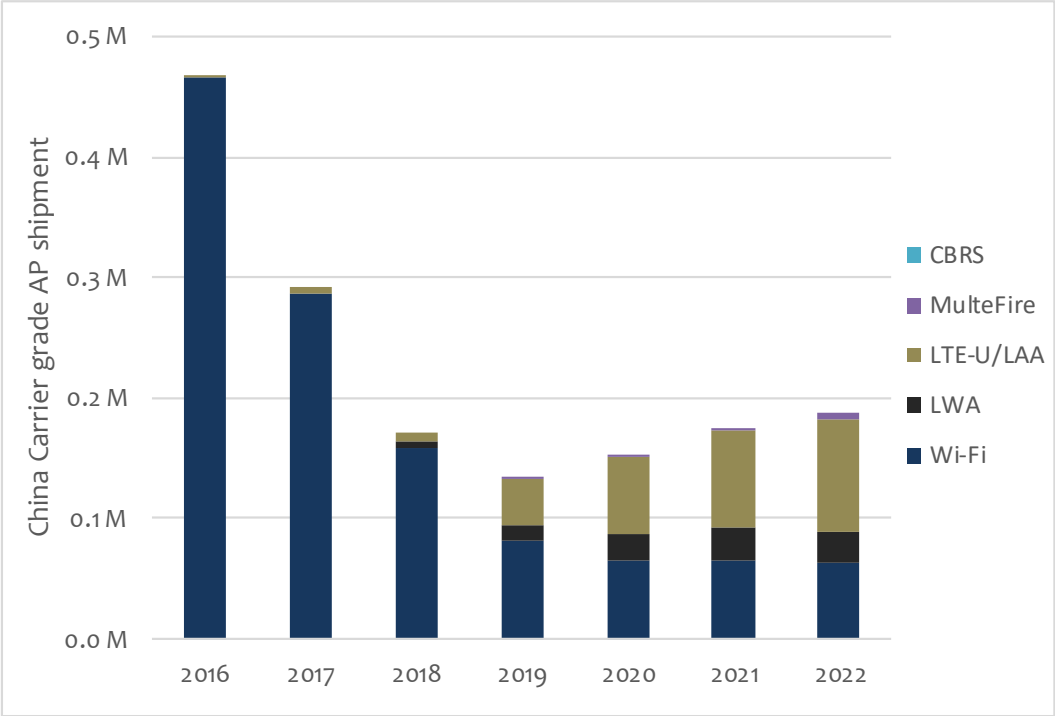


Source: Mobile Experts

Chart 25: Carrier Unlicensed Access Equipment, Europe, 2016-2022

China

Consistent with our view last year, Mobile Experts forecasts a significant decline in the traditional carrier Wi-Fi infrastructure shipments in China. With 3GPP standards-based LTE technologies coming into view, the major mobile operators are diverting capital dollars towards traditional 3GPP standards based small cells. While we had expected China Mobile with a significant installed base of Wi-Fi access points to leverage LWA to augment network capacity, we have seen a strong evidence of LWA demand from Chinese operators. Mobile Experts believes that China Mobile and other Chinese operators may focus their attention towards the 3.5GHz band in preparation for 4.5G LTE-Advanced Pro network rollouts and eventually onto 5G. Instead of focusing on unlicensed spectrum, China Mobile may leverage LTE-Advanced Pro features like Carrier Aggregation, 256 QAM and 4x4 MIMO strictly on licensed spectrum bands. Operators with limited licensed spectrum holdings like China Unicom and Telecom may be more inclined to adopt LAA. Our current forecast is biased towards this dynamic of China Mobile focusing on licensed spectrum for Carrier Aggregation and China Unicom and Telecom opportunistically leveraging LAA.

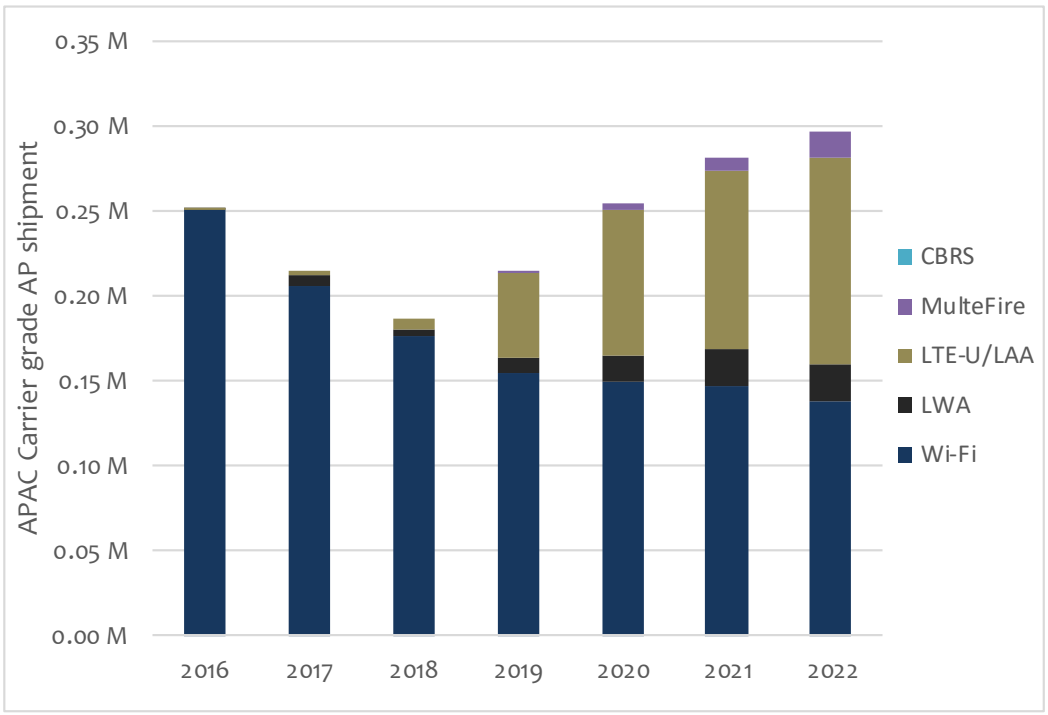


Source: Mobile Experts

Chart 26: Carrier Unlicensed Access Equipment, China, 2016-2022

Asia Pacific (excluding China)

Some of the leading mobile markets in Asia-Pacific, notably Korea and Japan, have already implemented LWIP schemes. However, this architecture has not gained much traction outside of Korea. The standards process in IETF working group and technical maturity has been slow to gain adoption. The complexity and dependency around Multipath TCP (MPTCP) connectivity on core network infrastructure and on client devices seems too burdensome for other operators. The 3GPP based LAA and LWA seems more likely path forward for most operators at this point. While carrier Wi-Fi investments wane, Mobile Experts forecasts the overall LTE-U and Carrier Wi-Fi access equipment shipment to grow 7% CAGR (2017-2022) with LAA taking precedence over LWA and MulteFire. We expect mobile operators with limited licensed spectrum holdings will look to LAA to enhance their network capacity as more LAA capable devices come to market in 2018 and 2019.

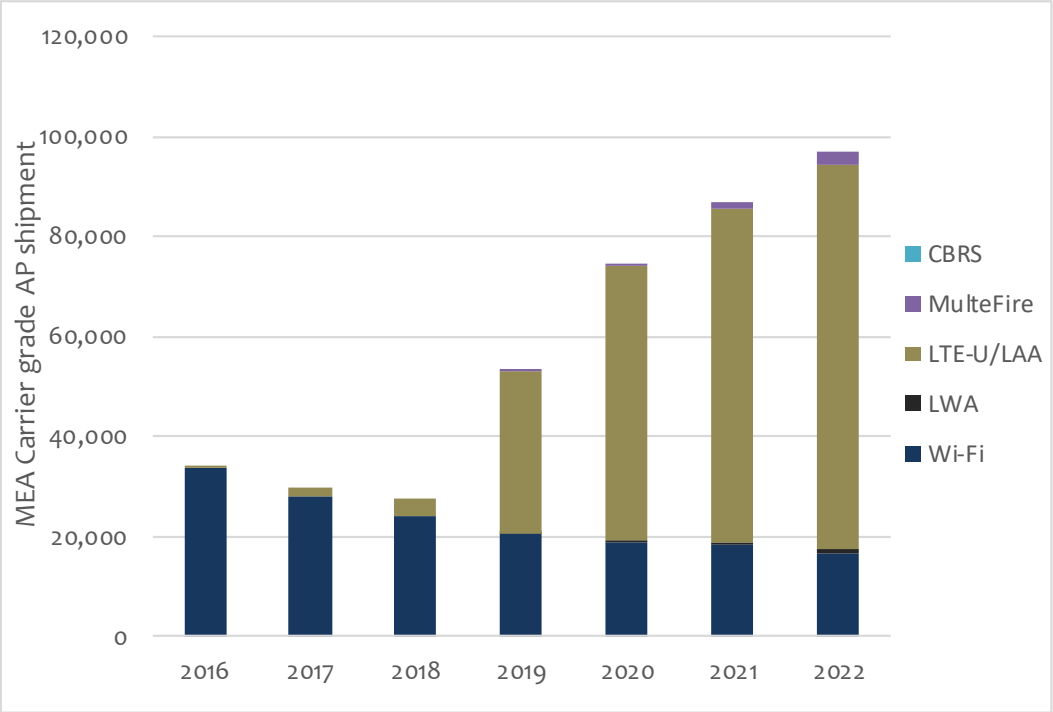


Source: Mobile Experts

Chart 27: Carrier Unlicensed Access Equipment, APAC, 2016-2022

Middle East/Africa

The Middle East/Africa (MEA) region is very diverse. The developed markets like Dubai, Turkey, and South Africa continue to advance their network capabilities and deploy latest LTE features. In Turkey, for example, all three major mobile operators are already marching towards LTE-Advanced Pro network rollouts. For these high-end segment of the region, Mobile Experts expects mobile operators to deploy LAA small cells along with high-end smartphone introduction to tout "Gigabit LTE" services over the next couple of years. For operators with limited licensed spectrum holdings in Africa, LAA small cells offer a scalable solution to increase network capacity where needed. Starting from a small base, Mobile Experts expects a robust growth overall with LAA making up almost 80% share of the total unlicensed carrier access equipment shipped in the region in 2022.

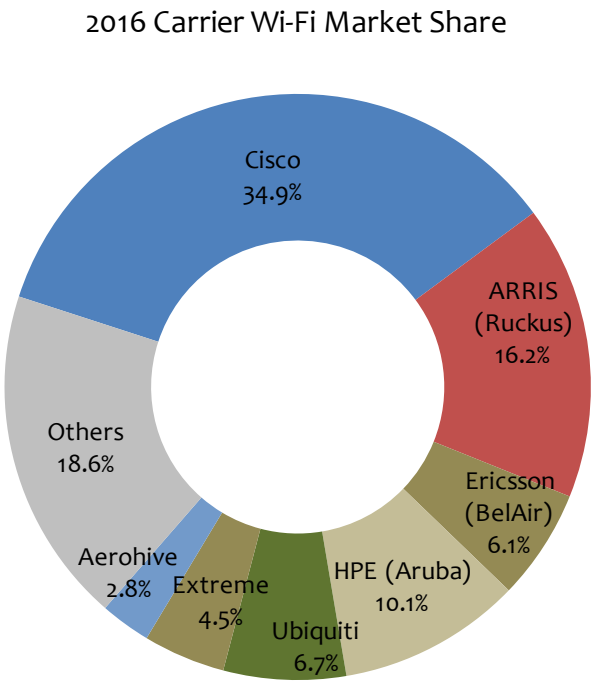


Source: Mobile Experts

Chart 28: Carrier Unlicensed Access Equipment, MEA, 2016-2022

7 MARKET SHARE

In this year's report, we have simplified the Carrier Wi-Fi market share figures. Instead of separating so-called "standalone" access point infrastructure separately from broadband CPE-enabled Wi-Fi equipment, we have simply combined and removed this nuance. The revised chart representing the 2016 market share for the Carrier Wi-Fi segment is shown below.



Source: Mobile Experts

Chart 29: Carrier Wi-Fi Revenue Share, 2016

As the market leader in the overall Wi-Fi industry including a much bigger Enterprise segment, Cisco leads the Carrier Wi-Fi segment with about 35% share of the $730M. Ruckus is in the second place with over 16% share. As the company goes through the complex multi-merger process (acquired by Brocade; soon to be divested by Broadcom as the part of Broadcom's Brocade acquisition; and then sold to ARRIS there soon after), it has lost some momentum in 2016. As a subsidiary of ARRIS with deep ties to broadband industry especially Cable, Ruckus may be in a good position to reap cable's increasing investments in wireless infrastructure. HPE/Aruba has been gaining market share in the service provider market, and is in the third place by our estimate.

It should be noted that traditional Wi-Fi market leaders including Cisco, HPE (Aruba), and others derive a bulk of their Wi-Fi revenue from the Enterprise segment which is much larger

than the Carrier segment. By our estimate, the Enterprise Wi-Fi market was about $5.3B in 2016, and is growing at about 7% annually. As the Carrier Wi-Fi declines, we expect smaller Wi-Fi vendors to focus their efforts in the enterprise space. For example, Ubiquiti has been focusing their product and sales strategy towards the Enterprise market.

Since the market for "LTE-based" unlicensed segment of the overall "carrier unlicensed" market is still very formative in its lifecycle, a market share chart for this particular segment of the overall market is not yet provided. As the market matures, we look forward to providing market share charts for the LTE-unlicensed sector, including LAA, LWA, MulteFire, and CBRS. For now, it is reasonable to expect that the major infrastructure vendors like Ericsson, Huawei, and Nokia to dominate the "LTE" side of the "carrier unlicensed access equipment" market.

8 COMPANY PROFILES

ACCURIS NETWORKS:

Accuris provides software solutions to facilitate roaming in cellular and Wi-Fi networks, and in particular the company focuses on mobile operators to enable authentication, billing integration and policy management services. The experience that Accuris brings in from its mobile customers in roaming solutions will aid in its drive for mobile/Wi-Fi integration. www.accuris-networks.com

ADTRAN:

Adtran is a broad telecom equipment vendor to mostly fixed service providers. The company has a broad product portfolio including residential gateways for optical and copper based networks. The company also offers a line of Wi-Fi access points, and "virtualized" wireless LAN through the use of cloud controller architecture, separating data plane and control plane to centralize management functions. www.adtran.com

AEROHIVE:

Aerohive offers a wide product line, ranging from access points to cloud management solutions. The company's primary focus centers on enterprise customers and identity-based network access. www.aerohive.com

ALEPO:

Alepo provides software solutions to put disjointed network pieces together. Founded in 1994, the company is growing quickly with early relationships with operators such as Vodafone, MTN, France Telecom, and Digicel. In particular, they assist these operators with access and security control, billing and policy control, and various roaming solutions for both mobile and unlicensed networks. www.alepo.com

ALTAI TECHNOLOGIES:

Altai provides a lineup of Wi-Fi networking solutions that centers on its directional "Super Wi-Fi" access point which is often used in outdoor applications for a long-range coverage. The company has installed systems throughout the developing world for local wireless service providers. www.altaitechnologies.com

ALVARION (ACQUIRED BY SUPERCOM)

Based in Israel, Alvarion has changed focus towards Wi-Fi systems. The company offers Wi-Fi offloading solutions, including the hardware for access points and controllers, as well as the software solutions for mobile integration. The company was recently acquired by SuperCom, a global provider of secure digital solutions for government, healthcare, public safety, and financial sectors. Alvarion was reportedly generating about $8M in annual sales in the recent years prior to the acquisition in June 2016. www.alvarion.com

APTILO:

Aptilo is a leading vendor in Wi-Fi integration software and services for the mobile core. Aptilo has taken the clear leading market share by serving most of the major mobile operators with Wi-Fi offloading solutions to facilitate billing and policy integration. www.aptilo.com

ARRIS:

Arris is a major cable infrastructure vendor, including CMTS and cable modems. As more Wi-Fi capabilities are embedded into broadband CPEs, Arris is increasingly seen as a trusted supplier of both cable and Wi-Fi equipment to the cable operators. It is reasonable to expect Arris to broaden wireless product portfolio as the cable operators increase their Wi-Fi network footprint and possibly into other wireless technologies in the unlicensed band use. www.arris.com

AVAYA:

Spun off from Lucent in 2000, was previously focused primarily on enterprise voice & data. They made their entrance to the Wi-Fi market at the 2014 Olympic Winter Games in Sochi, and later secured the sponsorship for San Jose's Avaya Stadium. They provide centralized WLAN controllers, indoor and outdoor APs, and system management software. www.avaya.com

BOINGO WIRELESS:

Boingo began offering Wi-Fi services to travelers in airports as far back as 2001. They recently signed a Hotspot 2.0 roaming agreement with Sprint that provides Sprint customers access to Boingo's hotspot networks at major US airports. The company is reportedly in a serious discussion with another major US mobile operator for a Hotspot 2.0 roaming agreement. The company has ventured into new businesses for growth including Distributed Antenna System (DAS) for mobile operators and network services to military bases. www.boingo.com

BROADCOM:

Broadcom is a leading chipset supplier to the Wi-Fi market (and many other segments of the communications market). Most major smartphones and access points use Broadcom chipset. With a broad portfolio of IP and chipset solutions in both mobile and Wi-Fi markets, the company is in a leading position in the carrier infrastructure market. In addition to the Wi-Fi chipset, the company has a product line dedicated to licensed small cells. www.broadcom.com

CABLEVISION (ACQUIRED BY ALTICE)

Cablevision is a major cable operator in the NYC tri-state region. The company has been an active participant in the carrier Wi-Fi space as one of the leading cable operators to adopt Wi-Fi to "extend" its broadband network. It offers Optimum Online, a network of Wi-Fi hotspots around the greater New York City metro area. It also launched FreeWheel service, a Wi-Fi only handset that leverages the Optimum Online hotspots for coverage. The company was recently acquired by Altice, a global cable and mobile operator with operating companies in Europe. In addition to Cablevision, Altice has also acquired Suddenlink, a US cable operator with networks in Texas and other "rural" states. Altice owns a second largest mobile operator in France, and has been an active player and observer of the fixed-mobile competition in Europe. www.optimum.net

CHARTER:

With a recent acquisition of Time Warner Cable and Bright House Networks, Charter is now the second largest cable operator in the US with 22 million household subscribers to fixed broadband and video services with a geographic footprint covering almost 50 million households from east to west coasts. With robust growth in the small business segment as well as strategic 'Cable WiFi' footprint acquired from Time Warner and Bright House, Charter is expected to be a significant player in the carrier infrastructure market in the unlicensed space. www.charter.com

CHINA MOBILE:

As the largest mobile operator in China and the world in terms of subscribers and network footprint, China Mobile has been an early adopter of leveraging Wi-Fi network for mobile data offload. The company has roughly 6 million Wi-Fi access points that can be upgraded, but specific plans for the upgrade have not been announced. www.chinamobileltd.com

CISCO:

Cisco is a dominant leader in the overall Wi-Fi infrastructure market with extensive global channel partnerships especially in the enterprise segment. Cisco has been moving aggressively to extend its lead into the service provider market with a portfolio of small cell and Wi-Fi access points. Cisco has several active programs to extend its wireless business with service providers beyond Wi-Fi into the unlicensed LTE space. Its recent membership to the MulteFire Alliance is a good guidepost of its intention to be an active player in the evolution of the Carrier Wi-Fi market. Clearly Cisco sees the service provider Wi-Fi opportunity as a way to extend its market footprint in the cable and mobile industries. With its broad portfolio of products ranging from core routing and switching extending to wireline and wireless access networks, Cisco can be an influential player in the Wi-Fi / LTE convergence in the unlicensed use. www.cisco.com

COMCAST:

Comcast is the largest US cable operator with about 24M fixed broadband household subscribers. The company has been moving aggressively in expansion of its 'xfinity' Wi-Fi service with over 14M homespots and hotspots. Although a majority of its public facing hotspots are dual SSID from residential CPE's, the company has deployed outdoor units along its cable plant in strategic locations. In addition to the CableWiFi roaming venture with other US cable operators, it has established trans-Atlantic roaming agreement with Liberty Global, a major cable operator in Europe and other regions. Besides the Wi-Fi ventures, the company is reportedly in the running for a licensed spectrum acquisition through the Incentive Auction as well as a possible MVNO play. www.comcast.com

DEVICESCAPE:

Devicescape offers a "curated" virtual network for amenity Wi-Fi and operators, in which they discover available open APs, stitching together an offload network for operators from private Wi-Fi, municipal Wi-Fi, transportation systems, and other available networks. Devicescape has developed the software to be able to automate the integration of disparate network elements into a useful offload solution, and they offer the management of the network as a service. www.devicescape.com

EDGEWATER WIRELESS:

Edgewater supplies access points for broad coverage applications as well as high-density urban applications, along with network management systems. The company has had some success with wireless service providers in developing countries that desire widespread Wi-Fi coverage. The company partners with solutions from Aptilo to facilitate interworking with other fixed and mobile networks. www.edgewater.com

ERICSSON:

Ericsson is a leading vendor of mobile infrastructure worldwide. The company made a big move into the Wi-Fi space with the acquisition of BelAir Networks. Besides the Wi-Fi product portfolio from Belair, Ericsson has a partnership with HPE (Aruba) for cross-selling HPE/Aruba Wi-Fi solutions into the service provider segment. With its broad portfolio of macro, small cell and Wi-Fi products, Ericsson is expected to lead deployment of HetNet solutions into the service provider segment. www.ericsson.com

EXTREME NETWORKS:

Extreme Networks has a line of Wi-Fi solutions from Zebra acquisition for selling into large venues. Its Wi-Fi products have been notably deployed at NFL stadiums. And, as an official NFL Wi-Fi analytics company, it has been active in selling Wi-Fi solutions as in-building wireless system into other large venue segments including hospitals and hotels. It is in process of acquiring Avaya assets from bankruptcy. www.extremenetworks.com

FEDERATED WIRELESS:

Formed in 2012, Federated Wireless is developing dynamic Spectrum Access Service (SAS) platform that is critical in use of the 3.5GHz CBRS band. The company's approach incorporates a network of radio sensors to alleviate possible interference with incumbent users of the band, including naval radars, satellite, and wireless ISPs. The company is headquartered in Arlington, VA.

FON:

FON has created a worldwide "crowdsourced" network of Wi-Fi access points where members share access to their residential or small-business Wi-Fi in order to gain access to others. The network has grown to more than 20 million "hotspots" or access points. The company has established partnerships with global telcos including BT, Deutsche Telekom, Softbank, Oi, and Telstra. www.fon.com

FORTINET (MERU):

Fortinet provides a Wi-Fi access point product line that emphasizes security feature. W-Fi AP products are seen as a product add-on to sell its security solution to service providers. Fortinet acquired Meru Networks in 2015. Meru had focused on providing virtualized solutions for the enterprise Wi-Fi market, and with solutions geared for stadiums and other public spaces has developed solutions compatible with Hotspot 2.0. www.fortinet.com

GOOGLE:

In 2015 Google made a move into the Wi-Fi First space announcing Project Fi, a subscriber service. Initially limited to one handset (the Nexus 6) the Google Fi service offers Wi-Fi calling, and falls back to MVNO service when Wi-Fi is unstable or unavailable. Google's MVNO structure is unique in that it allows users to leverage both Sprint and T-Mobile networks. The company has also made moves into the public Wi-Fi space by backing Sidewalk Labs, which is leading the LinkNYC project to convert old pay phone stands to hotspots in New York City. Moreover, the company has been leading the 3.5GHz CBRS ecosystem and has developed the critical SAS system for the use of 3.5GHz CBRS bands. www.google.com

HUAWEI:

Huawei is a global supplier of wireless telecom hardware, and has a leading market share position in licensed-band radio access networks in developing countries. The company has integrated Wi-Fi radio hardware into its "AtomCell" line of licensed small cells and has close relationships in China which all but guarantees a solid market share position as licensed/unlicensed small cells are deployed. Huawei is also a major driving force behind the IEEE 802.11ax standard effort. www.huawei.com

HP ENTERPRISE (ARUBA):

HP is a significant player in the enterprise Wi-Fi space and is overlapping a bit into the carrier Wi-Fi market. With the Aruba acquisition in 2015, HP Enterprise immediately jumped into a top-tier market leader in the Wi-Fi network equipment space. With a special focus on campus-type enterprise product portfolio from Aruba, HPE has made significant inroads in the enterprise segment, including indoor and outdoor campus solutions. Many of the enterprise features can be translated into the service provider segment, and HPE has had success selling into the service provider segment in Middle East and Asia-Pacific. www.hpe.com

INTEL:

Intel provides chipset solutions into smartphone OEMs as well as small cell vendors. Intel is also very active in MulteFire and 3.5GHz CBRS development. With its broad reach into smartphone devices, licensed and unlicensed small cells as well as data center solutions, it is in a good position to influence the broader HetNet evolution as service providers look to harness both licensed and unlicensed bands. www.intel.com

MARVELL:

Marvell provides SoCs for the baseband and radio processing for Wi-Fi access points, and has launched an 802.11ac Wave 2 with MU-MIMO. The company has acquired Kinoma in an effort to gain traction in the Internet of Things and M2M market. www.marvell.com

MITEL (ACQUIRED MAVENIR/STOKE):

Mavenir Systems acquired Stoke, and the combined company provides software-based networking solutions that enable carriers to deliver next generation services over 4G LTE networks and "untrusted" Wi-Fi networks. The company has a broad portfolio of LTE and Wi-Fi network elements, and the product lines can be sold "as a service." www.mavenir.com

MEDIATEK:

Mediatek is a fabless semiconductor supplier that has grown its share of the chipset market for smartphone processors through strong penetration of the Chinese "white box" market for handset designs. The company has introduced a 5-in-1 combo chip with LTE, Wi-Fi (up through 802.11ac Wave 1), camera and video playback, Bluetooth, GPS, and FM transceivers all with concurrent operation. www.mediatek.com

MOTOROLA SOLUTIONS:

Despite its focus on enterprise Wi-Fi solutions and in particular on the retail space, Motorola Solutions has been able to supply significant numbers of network elements into initial operator deployments during early disjointed service provider Wi-Fi development. www.motorolasolutions.com

NOKIA NETWORKS (ACQUIRED ALCATEL-LUCENT):

Nokia Networks continues to address the mobile infrastructure market. With the acquisition of Alcatel-Lucent, the company has been active in the small cells market. Nokia is a leading member of the MulteFire Alliance, and has a comprehensive small cell offering that supports the various flavors of LTE unlicensed technologies. The company has a large installed base of 3G and LTE base stations, and has integrated Wi-Fi with ANDSF and other intelligence to provide HetNet networks that can steer traffic between licensed and unlicensed radios. www.nokia.com

PERASO:

Persaso is an early pioneer in the WiGig 60 GHz technology space. The company is a fabless semiconductor company based in Toronto and with chipset products for client devices as well as wireless infrastructure. www.perasotech.com

QUALCOMM:

Qualcomm Atheros is a leading chipset vendor in the Wi-Fi market. Along with its parent, Qualcomm is a major technology supplier into both licensed and unlicensed bands. Qualcomm is a leading vendor of the LAA, LTE-U, and MulteFire technologies. www.qualcomm.com

REPUBLIC WIRELESS:

Republic Wireless is a "poster child" of the "Wi-Fi first" operator. It provides a full mobile service based on the "Wi-Fi first" business model where it looks to divert traffic onto Wi-Fi first whenever open Wi-Fi network access is available. When Wi-Fi is not available, it falls back to cellular. The company has an MVNO arrangement with Sprint for the cellular access. They offer service tiers ranging from a free Wi-Fi Only mode to plans with unlimited talk/text & data via MVNO agreements. Currently, users must purchase a phone from Republic. The company has recently broadly expanded smartphone portfolio beyond the Motorola brand with its software innovation that does not require a pre-installation of Republic's "connection manager" software on devices. www.republicwireless.com

RUCKUS WIRELESS (ACQUIRED BY BROCADE, BEING SOLD TO ARRIS):

Ruckus Wireless is now a wholly-owned subsidiary of Brocade. It has been among the fastest-growing suppliers of Wi-Fi equipment into the service provider Wi-Fi market. The company was recently acquired by Brocade. The company provides a full range of access points, gateways, and software solutions, and is actively targeting the "hybrid" market with active developments in multiple market segments including MulteFire and 3.5GHz CBRS. www.ruckuswireless.com

SPIDERCLOUD:

SpiderCloud focuses on scalable in-building RAN and tools for managing large networks of radios. They have announced commercial successes with Cisco in the small cell market. SpiderCloud has introduced both LTE-U/LAA and CBRS small cells. It has launched CBRS radio module that plugs into Cisco outdoor Wi-Fi access point. This product is being trialed at a major cable operator field trial in 2017. www.spidercloud.com

T-MOBILE:

Seeking to break out of their role as a lower-tier mobile operator, T-Mobile has been aggressive expand its network footprint and capacity. T-Mobile has been an innovator in deployment of personal cellspot Wi-Fi and later LTE femtocells. T-Mobile has been very public about its plan to deploy LTE-U technology to greatly expand capacity. www.t-mobile.com

TROPOS (ACQUIRED BY ABB):

Tropos has been an innovator in the wireless mesh networking. Its gears are typically deployed in outdoors. The company was acquired by ABB in 2012 to target utility and power industry sectors as their wireless solution. www.t-mobile.com

UBIQUITI NETWORKS:

Ubiquiti provides solutions for point-to-point connections and backhaul. They offer some proprietary features for uplink/downlink duplexing and cognitive radio features to improve performance. They offer have some low-cost Wi-Fi network solutions for developing markets, some offerings for IoT/M2M and security, as have recently begun to expand into the enterprise AP market with both indoor and outdoor products. With its low-cost products, it is one of the leaders in the retails sector. www.ubnt.com

VIVINT:

Ubiquiti provides solutions for point-to-point connections and backhaul. They offer some proprietary features for uplink/downlink duplexing and cognitive radio features to improve performance. They offer have some low-cost Wi-Fi network solutions for developing markets, some offerings for IoT/M2M and security, as have recently begun to expand into the enterprise AP market with both indoor and outdoor products. With its low-cost products, it is one of the leaders in the retails sector. www.ubnt.com

WEFI:

WeFi offers software solutions for multiple aspects of Wi-Fi networks, including the aggregation of millions of public Wi-Fi APs, integration of Wi-Fi operation with existing networks, ANDSF integration and clients, and mobile data analytics on Wi-Fi networks. www.wefi.com

WI-FI ALLIANCE (WFA):

Wi-Fi Alliance is an industry trade group which promotes the "Wi-Fi" brand, as well as certifying products to be compliant with Wi-Fi standards as well as with Hotspot 2.0 and other requirements. Wi-Fi Alliance provides the "Passpoint" trademark for products which comply with the Hotspot 2.0 requirements. The group is currently in charge of coming up with LTE-U/Wi-Fi coexistence test plan. In a way, it has become a "gatekeeper" to LTE-U deployments in the US. The test plan is now expected to be completed in September 2016. www.wi-fi.org

WIRELESS BROADBAND ALLIANCE (WBA):

WBA is an industry organization made up of a diverse group of service providers, promoting specification and promotion of "carrier grade" services over Wi-Fi networks. The group develops specifications such as the Hotspot 2.0 (also known as Next Generation Hotspot in WBA parlance) to enable seamless interworking on Wi-Fi networks. www.wballiance.com

XIRRUS:

Xirrus offers indoor and outdoor APs for carrier-grade Wi-Fi applications in stadiums and other large venues. The company has developed RF arrays for applications in very high user density environments, and their recent products are Hotspot 2.0 compatible. www.xirrus.com

9 ACRONYMS

2G: Second Generation Cellular

3G: Third Generation Cellular

3GPP: Third Generation Partnership Project

4G: Fourth Generation Cellular

802.1x: A security platform standard established by IEEE.

802.11: An umbrella standard which encompasses multiple unlicensed communications standards within the IEEE.

802.11a/b/g: Early generations of the 802.11 standard.

802.11n: The current generation of the 802.11 standard.

802.11ac: The generation of the 802.11 standard introduced in 2013.

802.11ad: An IEEE standard for 60 GHz short-range communications.

802.11ah: An IEEE standard for unlicensed communications below 1 GHz.

802.11ax: A future IEEE standard for very high throughput in Wi-Fi.

802.11i: An IEEE security specification for Wi-Fi networks.

802.11k: An IEEE standard for radio resource management to assist in limited mobility.

802.11r: An IEEE standard for rapid transition from one AP to another.

802.11u: The IEEE standard associated with Hotspot 2.0.

AAA: Authentication, Authorization, and Accounting (typically refers to the server which performs these functions).

AC: Alternating Current or Access Controller.

ACK: Acknowledgement.

AES: Advanced Encryption Standard.

ANDSF: Access Network Discovery and Selection Function.

Android: Google's mobile device operating system.

AP: Access Point (often referring to Wi-Fi access point)

APN: Access Point Name

ARPU: Average Revenue Per User

BSC: Base Station Controller

BTS: Base Transceiver Station

Bits/Hz/sec: Digital bits transmitted per Hertz of bandwidth per second

CA: Carrier Aggregation

CBRS: Citizens Broadband Radio Service, a shared wireless broadband use of the 3550-3700 MHz (3.5GHz) band in the US

CPE: Customer Premise Equipment (e.g., cable modem, broadband gateway)

dBm: Decibels of power relative to 1mW

DRS: Distributed Radio System

DSL: Digital Subscriber Line

EAP: Extensible Authentication Protocol.

EAP-AKA: EAP via Authentication and Key Agreement.

EAP-SIM: EAP via Subscriber ID Module.

EAP-TLS: EAP via Transport Layer Security.

EAP-TTLS: EAP via Tunneled Transport Layer Security.

EMEA: Europe, Middle East and Africa

eNB: eNodeB, or the radio access node for LTE

EPC: Evolved Packet Core.

ePDG: Evolved Packet Data Gateway.

GAA: General Authorized Access, applicable for the 3.5GHz shared spectrum, the lowest priority access, similar to unlicensed spectrum use

GB: Gigabyte

Gbps/km2: Gigabits per second per square kilometer

GHz: Gigahertz

GSM: Global System for Mobile communications, a 2G radio interface

GTP: GPRS Tunneling Protocol

GW: Gateway (normally referring to a femto gateway)

HARQ: Hybrid Automatic Repeat Request

HetNet: Heterogeneous Network

HEW: High Efficiency Wireless (now renamed 802.11ax)

HLR: Home Location Register.

HSPA: High Speed Packet Access

HSPA+: A subsequent evolution of HSPA with higher throughput

HSS: Home Subscriber Server

Hz: Hertz (cycles per second)

IEEE: Institute of Electrical and Electronics Engineers

IETF: Internet Engineering Task Force

IKEv2: Internet Key Exchange (version 2)

IP: Internet Protocol

IPSec: Internet Protocol Security

IPv4: Internet Protocol version 4

IPv6: Internet Protocol version 6

I-WLAN: Interworking for Wireless Local Area Networks.

LAN: Local Access Network

LTE-A: LTE Advanced, a higher bandwidth version of LTE

LAA: LTE-License Assisted Access, a 3GPP-compliant "official" LTE-U technology

LTE: Long Term Evolution, a "4G" radio interface based on orthogonal frequency division multiplexed data

LTE-U: LTE-Unlicensed, an "unofficial" technology to run LTE waveform on 5GHz unlicensed spectrum band

LWA: LTE/Wi-Fi Aggregation (use of LTE signals on both licensed control channels and licensed data channels, and Wi-Fi signals on unlicensed data channels).

MAC: Media Access Control layer

MHz: Megahertz

MIMO: Multiple Input, Multiple Output

MNO: Mobile Network Operator

MSO: Multi-Service (or System) Operator (reference to a cable operator)

MVNO: Mobile Virtual Network Operator

MulteFire: Standalone LTE-U technology whereby both control and data plane traffic flows in an unlicensed band

MU-MIMO: Multi-User MIMO.

NGH: Next Generation Hotspot (Hotspot 2.0)

OEM: Original Equipment Manufacturer

OFDM: Orthogonal Frequency Division Multiplexed

PAL: Priority Access License, applicable for the 3.5GHz band, second highest priority in use of the 3.5GHz shared spectrum

Passpoint: A certification stamp for Hotspot 2.0 equipment, administered by Wi-Fi Alliance

PC: Personal Computer

QoS: Quality of Service

RAN: Radio Access Network

RF: Radio Frequency

SAS: Spectrum Access System, a software system to coordinate spectrum sharing (although it can be applied across all shared spectrum, its use is primarily focused on 3.5GHz CBRS)

SIP: Session Initiation Protocol

SNR: Signal-to-Noise Ratio

SSID: Service Set Identification

TD-LTE: Time Domain based Long Term Evolution

UE: User Equipment

VAR: Value Added Reseller

W: Watts

WCDMA: Wideband Code Domain Multiple Access, a 3G radio interface

Wi-Fi: Wireless Fidelity (802.11 data communications)

WISP: Wireless Internet Service Provider

WLAN: Wireless Local Area Network

10 METHODOLOGY

To create estimates and forecasts for the Carrier Wi-Fi market, Mobile Experts relied on direct input from more than 70 industry sources, with many different mobile, cable, and ISP operators contributing to the overall analysis to give a detailed global view of the market. Mobile Experts built a "top down" forecast based on direct input from mobile operators and based on trends in end-user demand for mobile services. Then, Mobile Experts built a "bottom up" forecast through discussions with OEMs, software developers, and semiconductor suppliers in the supply chain. Roughly 40 suppliers, integrators, and OEMs participated in this phase of the survey. Mobile Experts also used financial disclosures from publicly traded companies to assemble a quantitative view of the equipment market.

Mobile Experts has investigated the entire ecosystem for Wi-Fi in public areas, with segmentation that is different than other market analysis. In this study, we cover Wi-Fi equipment deployed by an "operator", meaning a company that provides a public wireless access service, as well as large venues such as stadiums, airports, military bases, and even city deployments. These non-carrier participants are included because Hotspot 2.0 enables all of these entities to interwork via roaming agreements in the same way, and the equipment is likely to look very similar.

Small cells with integrated Wi-Fi are included in this analysis. In particular, Mobile Experts has assumed that many indoor licensed small cells will also include Wi-Fi semiconductors. This forecast estimates the number of these Wi-Fi APs and the minority portion of the small-cell ASP which is devoted to unlicensed operation.

SCOPE OF PUBLIC WI-FI:
Public Wi-Fi includes deployment of Wi-Fi networks by mobile operators, cable operators and other multi-service operators (MSOs), and deployment in large venues such as major hotels, stadiums, college campuses, and other public buildings. Transportation, metropolitan, and other applications are included because of the intent to serve public Wi-Fi: railways, aircraft, DAS neutral hosts, and over-the-top providers. Backhaul via Wi-Fi, Enterprise Wi-Fi systems, and private Wi-Fi networks are not included in the scope of this market study.

NOTES ON MARKET SHARE:
In the Mobile Experts forecast, "market share" designates the proportion of market revenue for each supplier. "Shipment share" denotes the proportion of total shipments from each supplier. In general, Mobile Experts uses market share for semiconductors and for software because revenue tracking is more straightforward than other measurements. However, in the case of network elements such as Access Points or Wi-Fi networks, the revenue from software and service creates confusion and "shipment share" provides a more trackable, straightforward metric.

Figures 21 through 24 give the detailed definitions for each category of equipment, for regions of the world, and for specific segments of Carrier Wi-Fi equipment.

North America:	USA and Canada
Latin America:	Mexico through South America, including Caribbean
Europe:	Western and Eastern Europe, including Russia
China:	China, including Tibet and Hong Kong
Asia Pacific:	India through Australia/Micronesia, excluding China
Middle East/Africa:	Pakistan and Turkey through Africa

Source: Mobile Experts

Figure 21. Detailed Definitions for Regions

EAP-SIM:	Extensible Authentication Protocol-by Subscriber Identification Module. This approach uses the SIM card, generally in a handset, to authenticate the user. An increasing number of tablets include SIM cards to take advantage of this approach.
EAP-AKA:	An extension of EAP-SIM to authenticate a user via Authentication and Key Agreement. In short, this is a variation on EAP-SIM for UMTS 3G mobile devices.
EAP-TLS:	Authentication using Transport Layer Security relies on certificates. The TLS protocol uses certificates from both the end-user device and the network to validate a two-way connection.
EAP-TTLS:	Authentication using Tunneled Transport Layer Security also relies on certificates, but in this case only the network must provide a certificate and the client may be validated through a secured tunnel.

Source: Mobile Experts

Figure 22. Detailed Technical Definitions for Specific Authentication Protocols

LTE Unlicensed	Known as LTE-U. Defined by the LTE-U Forum and led by Verizon in cooperation with Alcatel-Lucent, Ericsson, Qualcomm Technologies, Inc., and Samsung. LTE-U base stations and consumer devices leverage unlicensed frequencies in the 5 GHz (UNII-1 and UNII-3) bands as data channels, with the LTE control plane operating across licensed frequencies. LTE-U is based on 3GPP's already published Release 10 and later specifications. LTE-U extends the benefits of LTE and LTE Advanced to unlicensed spectrum, but without a Listen-Before-Talk schema.
CSAT	Carrier Sensing Adaptive Transmission essentially uses a duty cycle to turn LTE on and off. The duty cycle can be adaptive but many examples refer to a 1/3 duty cycle for LTE transmission.
Listen-Before-Talk	A mechanism for contention mitigation. LBT systems can more fairly share spectrum with heterogeneous standards and not dominate a wireless channel.
Licensed-Assisted Access	Known as LAA. Like LTE-U, LAA leverages unlicensed spectrum for data in the 5 GHz (UNII-1 and UNII-3) bands as data channels, with the LTE control plane operating across licensed frequencies. LAA offers support for Listen-Before-Talk. Ratification by 3GPP is expected in Release 13 in March 2016.
LTE/Wi-Fi Aggregation	Known as LWA. LTE/Wi-Fi Aggregation uses Wi-Fi (802.11ac, etc.) in 5 GHz data channels, with the LTE control plane operating across licensed frequencies. Because it uses standard Wi-Fi protocols, it is less likely to disrupt existing systems. Ratification by 3GPP is expected in Release 13 in March 2016.

Source: Mobile Experts

Figure 23. Detailed Technical Definitions of Access Technologies